Project no. TREN/07/FP6AE/S07.71574/037180 IFLY

iFly

Safety, Complexity and Responsibility based design and
validation of highly automated Air Traffic Management

Specific Targeted Research Projects (STREP)

Thematic Priority 1.3.1.4.g Aeronautics and Space

iFly Deliverable D5.2
Analysis of conflict resolution needs of the A^3 operational concept

Version: Final (1.2)

Authors: N. Kantas (UCAM), **J.M. Maciejowski** (UCAM), A. **Lecchini-Visintini** (ULES), **G. Chaloulos** (ETHZ), **J. Lygeros** (ETHZ), **I. Roussos** (NTUA), **A. Oikonomopoulos** (NTUA), **K. Kyriakopoulos** (NTUA), **P. Casek** (HNWL)

Start date of project: 22 May 2007 Duration: 51 months

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	

DOCUMENT CONTROL SHEET

Title of document: *Comparative Study of Conflict Resolution Methods*

Authors of document: *N. Kantas, J. Maciejowski, A. Lecchini-Visintini, G. Chaloulos, J. Lygeros, I. Roussos, K. Kyriakopoulos, P. Casek*

Deliverable number: *D5.2*

Project acronym: *iFly*

Project title: *Safety, Complexity and Responsibility based design and validation of highly automated Air Traffic Management*

Project no.: *TREN/07/FP6AE/S07.71574/037180 IFLY*

Instrument: *Specific Targeted Research Projects (STREP)*

Thematic Priority: *1.3.1.4.g Aeronautics and Space*

DOCUMENT CHANGE LOG

Version #	Issue Date	Sections affected	Relevant information
0.1	01.03.2008	All	First Draft
0.2	20.05.2008	All	Second Draft
0.3	01.07.2008	All	Third Draft
0.9	27.09.2008	All	Incorporated all comments on chapters
1.0	01.10.2008	All	Minor Changes
1.1	29.01.2010	All	Incorporated project review comments
1.2	24.02.2011	All	Final EC review

Version 1.0		Organisation	Signature/Date
Authors	N. Kantas	UCAM	
	J.M. Maciejowski	UCAM	
	A. Lecchini-Visintini	ULES	
	G. Chaloulos	ETHZ	
	J. Lygeros	ETHZ	
	I. Roussos	NTUA	
	A. Oikonomopoulos	NTUA	
	K. Kyriakopoulos	NTUA	
	P. Casek	HNWL	
Internal Reviewers	H. Blom	NLR	
	C. Foster	NATS	
External Reviewers	U. Voelckers	Independent	
	P Hotham	SESAR	
	K. A. Gryc	EC	

iFly, Work Package WP5, D5.2
Analysis of conflict resolution needs of the A^3 operational concept

February 25, 2011

Abstract

This is the second deliverable of the work package WP5 of the project iFly. The purpose of this report is to identify the conflict resolution requirements imposed by the novel ATM concepts developed under WP1 and WP2, as well as the resources that the concept can make available for conflict resolution tasks (in terms of communication, computation, stakeholder roles, etc.). The aim of this report is also to compare the advanced conflict resolution methods identified in deliverable D5.1, versus these requirements and suggest algorithms for the novel ATM concepts developed.

Contents

List of Acronyms

$\mathbf{A}^3$	**A**utonomous **A**ircraft **A**dvanced
ACAS	**A**ircraft **C**ollision **A**voidance **S**ystem
ADS-B	**A**utomatic **D**ependent **S**urveillance **B**roadcast/Contract
ASAS	**A**irborne **S**eparation **A**ssurance **S**ystem
ATC	**A**ir **T**raffic **C**ontrol
ATM	**A**ir **T**raffic **M**anagement
AZ	**A**lert **Z**one
CD	**C**onflict **D**etection
CDR	**C**onflict **D**etection and **R**esolution
CLFC	**C**losed **L**oop **F**eedback **C**ontrol
ConOps	**Con**cept of **Op**eration**s**
CR	**C**onflict **R**esolution
ETH	**E**idgenössische **T**echnische **H**ochschule
FMS	**F**light **M**anagement **S**ystem
HF	**H**uman **F**actor
ISS	**I**nformation **S**haring **S**ystem
MC	**M**onte **C**arlo
MCMC	**M**arkov **C**hain **M**onte **C**arlo
MFF	**M**editerranean **F**ree **F**light
MPC	**M**odel **P**redictive **C**ontrol
NF	**N**avigation **F**unctions
NTUA	**N**ational **T**echnical **U**niversity of **A**thens
OLFC	**O**pen **L**oop **F**eedback **C**ontrol
PAZ	**P**rotected **A**irspace **Z**one
PBA	**P**erformance **B**ased **A**irspace
RBT	**R**eference **B**usiness **T**rajectory
RTA	**R**equired **T**ime of **A**rrival

RVSM	**R**educed **V**ertical **S**eparation **M**inima
SESAR	**S**ingle **E**uropean **S**ky **A**TM **R**esearch Programme
SMC	**S**equential **M**onte **C**arlo
SSAS	**S**elf-**S**eparation **A**ir **S**pace
STCA	**S**hort-**T**erm **C**onflict **A**lert
SWIM	**S**ystem **W**ide **I**nformation **M**anagement
TCAS	**T**raffic Alert and **C**ollision **A**voidance **S**ystem
TFM	**T**raffic **F**low **M**anagement
TMA	**T**erminal **M**aneuvering **A**rea
TP	**T**rajectory **P**rediction
UCAM	**U**niversity of **Cam**bridge
MAGHP	**Multi-Airport, Ground-Holding Problem**
SAGHP	**Single-Airport, Ground-Holding Problem**
GTFM	**Generalised Traffic Flow Management**

1 Introduction

Over the recent years there has been an increase in the traffic load of the current Air Traffic Management (ATM) system. This motivated the development of new methods in order to cope with the projected increase of the demand for air traffic in the future. Earlier research efforts in HYBRIDGE focused on investigating successful mathematical methods from other areas, such as robotics, finance, communications etc., in order to provide a framework and set of tools to deal with the problem of increased traffic levels in ATM. This effort has lead to project iFly, whose main purpose is to apply and further develop the mathematical methods of HYBRIDGE in order to provide an airborne self separation design for en-route traffic and propose an advanced automated airborne ATM design. Such an automated ATM design for en-route traffic aims to manage a three to six times increase in current en-route traffic levels, while maintaining maximum safety.

1.1 Current ATM design

Increasing air traffic in limited airspace with maximum safety requires careful planning and intelligent on line management of the aircraft positions and velocities. A conflict occurs when two or more aircraft present at some limited airspace come close enough, so that dangerous aerodynamic instability occurs or the risk of collision is high. In current Air Traffic Control (ATC) the goal of Conflict Detection (CD) and Conflict Resolution (CR) is to make a prediction whether a conflict is likely to occur in the future, communicate the detected conflict to an operator and assist in the resolution of the conflict. The human operators involved for the detection and resolution of conflicts can be either a pilot or a controller. These are assisted also by systems like the Traffic Alert and Collision Avoidance System (TCAS) and the controller's Short-Term Conflict Alert (STCA).

Given some intent flight information and radar measurements a conflict detection procedure is executed with a view to detecting impending conflicts. ATC may then be informed by a suitable alerting mechanism. Using the radar information received at some ground based Information Sharing System (ISS) and accurate models of an aircraft's motion, ATM should resolve the possibility of any two or more aircraft coming close to each other. When this cannot be avoided and a conflict is detected the pilot is provided with an advisory of CR manoeuvres. For example, when approaching a Terminal Manoeuvring Area (TMA) CR manoeuvres are provided by the controller or in en route cases by ATM systems like TCAS.

1.2 iFly Proposed design cycle

Airborne self separation is a core concept of the ATM system designed by iFly, where for en route flight ground ATC support is limited. The design process is split in two stages. First we focus on the completely autonomous and decentralised case, described by the Autonomous Aircraft Advanced (A^3) concept of operation. According to A^3 it is assumed that all aircraft are effectively flying through unmanaged airspace. Instead of the current practice of receiving ATC service from ground each aircraft is made responsible for self separation. There may be monitoring by ground/external surveillance systems and data communication available directly between aircraft or through the ground, but there will be no ATC services provided to the aircraft while they are inside unmanaged airspace. iFly aims to evaluate and assess A^3 according to issues concerning technological readiness, computational complexity, human operators and airline response, performance and risk, or environmental efficiency etc. Any drawbacks identified during designing an ATM system according to A^3 will be used as input to the second design stage, in which in addition to self separation the aircraft can also rely on ground ATC support. This second design phase is envisioned as a first step toward fitting autonomous aircraft (the topic of the A^3 concept) into the wider SESAR concept of operations.

1.3 WP5 Contribution

As far as WP5 is concerned, we are interested in suggesting efficient algorithms to perform CR tasks for a number of aircraft present in some airspace area under the A^3 concept of operations. In our previous Deliverable D5.1 [8] we have presented a review of current state of the art algorithms that can be used for Conflict Resolution. These algorithms came from a diverse range of fields including non ATM areas of research, such as control and optimisation for robotics, transport, or operations research problems. In order to suggest successful algorithms for A^3, we have identified realistic CR requirements that should be fulfilled by the candidate algorithms. Especially those proven successful yet only in non ATM fields have been carefully chosen to address a safety critical and regulated industry such as ATM. In addition, we tried to ensure that the suggested algorithms can be designed to be also compatible with the concepts developed in parallel research efforts, such as the SESAR and NextGen concepts of operations. In this report, therefore, we also discuss briefly additional CR issues that will need to be addressed to fit the autonomous A^3 aircraft into the wider SESAR concept. These preliminary thoughts will be fleshed out in more detail later in the iFly work-flow.

1.4 Interaction with other Work Packages

The operational requirements and the human responsibilities of A^3 have been studied in parallel by WP1 and WP2 respectively. We shall use deliverables D1.1, D1.3 and D2.1, [20, 11, 3], as inputs to this deliverable. Apart from the issues addressed in these deliverables, we shall raise additional issues such as computational complexity, general applicability of the algorithms and the role of data communication in designing algorithms for A^3 as well as technological readiness.

Furthermore, we shall provide some motivation for further fundamental research. This has encouraged interaction with Work Packages 3 and 7, which also involve mathematical research on issues related to ours. We feel that such an attempt to carry on further fundamental research is critical as it can back up any ATM design with theoretical guarantees of performance and capabilities. Given that these CR algorithms are computationally expensive, improved analytical solutions might enable improvement of orders of magnitude in terms of the performance of the algorithms for CR modules. Also, it might prove useful for the certification process.

1.5 Objectives of this deliverable

In this deliverable, we shall focus on the requirements for the task of Conflict Resolution. Using all the inputs provided from WP1 and WP2 deliverables so far [20, 11, 3], we aim to identify these requirements and formulate the CR problem suitably. This will eventually provide a set of criteria so that existing, modified or new CR algorithms can be compared. A review of current research in the area of Conflict Resolution approaches can be found in our previous Deliverable D5.1 [8]. Taking that as an additional input, we shall propose algorithms to meet the identified requirements under A^3 and suggest issues for further development. Note that describing and investigating the suggested methods in detail is beyond the scope of D5.2; this is expected from future deliverable D5.3. This deliverable is rather meant to analyse the requirements assumed under A^3 and then to use these as criteria to make recommendations.

1.6 Organisation of this deliverable

This report is organised as follows: In Section 2 we will identify the requirements for CR under A^3. In Sections 3, 4, 5 we shall propose CR methods for each size of the time horizon, in which the conflict has to be resolved (long term, mid term and short term respectively) and discuss how these methods fulfil the specific requirements presented in Section 2. These methods have been selected from the exhaustive survey in deliverable D5.1, [8]. Finally, in Section 6 we make our recommendations along with some concluding remarks.

2 Requirements and Operational Considerations

In this section we shall present the requirements and operational considerations for A^3 as seen in [20]. We shall be considering the en-route part of a flight where airborne self separation is achieved using the iFly A^3 autonomous aircraft advanced concepts discussed in the previous section and focus more on the autonomous aircraft concept. We will also briefly discuss considerations that arise when trying to introduce A^3 aircraft into the wider SESAR concept, where additional ground support is available. According the A^3 ConOps, this part of the flight consists of the whole phase between the departure and destination TMAs and lies in a so-called Performance Based Airspace (PBA). Within this airspace the self-separation capable aircraft can fly according to the Autonomous Flight Rules, i.e., they are responsible for the ATM separation from other traffic and obstacles. The A^3 scope is further limited to the case when all aircraft in the PBA are self-separation capable.

Within the A^3 ConOps, an autonomous aircraft flying through PBA has two main objectives:

1. **Performance** considering:
    - *Global ATM safety and effectiveness* which is expressed in terms of various strategic (flow) constraints.
    - *Own flight effectiveness* reflected through different levels of trajectory and manoeuvres optimization.
2. **Own aircraft safety** ensured by conflicts and hazards avoidance systems.

Although WP5 is mainly focusing on the systems related to the own aircraft safety, some global ATM safety and performance aspects are also addressed within this document, e.g. a flight constraint at the entry point of the destination or TMA.

The airborne system described in the A^3 ConOps aims to provide safe self separation and trajectory management functionalities. It does not consider the Collision Avoidance capability that prevents a collision in the case of loss of separation. In fact, the presence of such a system such as TCAS onboard is assumed in the role of an independent safety backup. The whole system is designed as a pilot's supporting tool, i.e., it support the flight crew by providing all information needed to build a high level of situation awareness and providing possible solutions in form of manoeuvres or trajectories.

The organisation of the remaining section is as follows: In Section 2.1 we shall present the A^3 concept of preserving safe separation via maintaining a Protected Airspace Zone for each aircraft. In Section 2.2 we will present a general operational definition of a conflict and the requirements for Conflict Detection. Finally we will present some general operational considerations for Conflict Resolution in Section 2.3 and the detailed requirements in Sections 2.4 and 2.5 by decomposing the CR problem into different levels.

2.1 A^3 Requirements for Protected Airspace Zone

Separation management is one of the main tasks of the ATM. The applicable separation minima are usually expressed in terms of a protection zone surrounding the aircraft and the goal of Separation Management is to avoid any incursion of surrounding hazards to this zone. Review of some possible approaches on how to define such a zone geometrically can be found in [20].

In A^3 an ATM intervention is usually initiated when a potential penetration of some hazard into the protection zone is predicted. Alternatively a supplementary alert zone could be defined and corrective action could be then initiated after an intrusion of another aircraft in this alert zone. However, this method is not considered within A^3.

Within A^3 each aircraft is considered to lie inside its Protected Airspace Zone (PAZ) which is of cylindrical shape, with its radius being defined by a minimum horizontal separation and the height by a minimum vertical separation. Nowadays, the typical value for en-route horizontal separation is 5nm, while vertical separation can be no less than 2000ft for an altitude of 1000ft to 40000ft, unless Reduced Vertical Separation Minima (RVSM) of 1000ft is applied. In order to accommodate a large factor increase of en-route capacity, the A^3 ConOps aims for a reduction over current minimum separation criteria. The target values will be established within the D1.3 report [11].

2.2 A^3 Requirements for Conflict Detection

According A^3 a conflict occurs when an aircraft PAZ, which is described above, is predicted to be penetrated by:

- Area(s)-to-avoid: a restricted area, weather hazard area, congested area, etc.[1]
- Other aircraft.

Multiple types of areas-to-avoid are anticipated, some of them playing only an advisory role, e.g. congestion areas, different kinds of weather hazards.

All Conflict Detection (CD) algorithms are based on some method of determining aircraft future trajectory from available data. Nevertheless, the reliability of such Trajectory Prediction (TP) is strongly dependent on the quality and the content of input information. The A^3 considers three levels of the surveillance information about other aircraft:

- **State information** consisting mainly of the position and speed vector data. This information allows only a limited prediction of the future trajectory based on the state extrapolation, which can be linear or more complex if a sequence of previous states is also available. It is anticipated that such prediction may be useful only for the look-ahead horizon of 5-6 minutes.

---

[1] Areas-to-avoid are determined by an external from the ASAS perspective application.

- **Intent information** based on the data-link intent message. This message allows a reconstruction of the 4D trajectory (3D path with time profile) for 15-20 minutes of the flight together with some estimate of the related inaccuracy.
- **Reference Business Trajectory (RBT)** is the updated flight path information for the whole remaining part of the flight (up to destination). It is used mainly by strategic systems, only own RBT being considered within the airborne applications.

Within the A^3 there are three independent CD modules running in parallel according to these different levels of gathered surveillance information:

- **State Conflict Detection** performs the short term conflict detection (up to 3-5 minutes) based on the state-based TP.
- **Intent Conflict Detection** performs the mid term (up to 15-20 minutes) conflict detection based on the intent-based TP. This module can also detect the situations with high complexity such as limited manoeuvrability that could potentially overload the CR modules or affect the robustness of the system.
- **Areas Conflict Detection** performs the long term detection (more than 30 minutes) between own RBT and areas-to-avoid provided by other systems (e.g., weather radar), or uploaded from ground.

The overview of the different CD and surveillance levels is given in Figure 1. All conflicts detected by any of the CD modules are provided to the integrative module called **Alert Logic**, that performs the interpretation and assessment of the situation and initiates the appropriate action. The functional architecture of the overall system is shown in Figure 2.

2.3 A^3 Requirements for Conflict Resolution

Figure 2 shows the ATM architecture of the A^3 concept of operation. When considering the Medium and Short term levels of the A^3 concept, self separation is maintained on board. Hence, the CR algorithms have to be decentralised and each aircraft acts as an autonomous agent, which acquires limited information on other agents' decisions either from the ground ISS or direct air to air communication or broadcast. Note that this information is not technologically proven to be completely reliable yet, which arises further complications. [8] presented a survey of methods to choose from, including some that deal with these problems.

Subsequent work in iFly, under WP8, will also consider how autonomous aircraft can be introduced into the wider SESAR concept. The process will only differ by adding automated ATC support from the ground. As far as CR resolution is concerned, the main difference compared to A^3 is that now one can employ centralised algorithms for resolving conflicts and potential algorithms that require a much higher amount of computation can be considered.

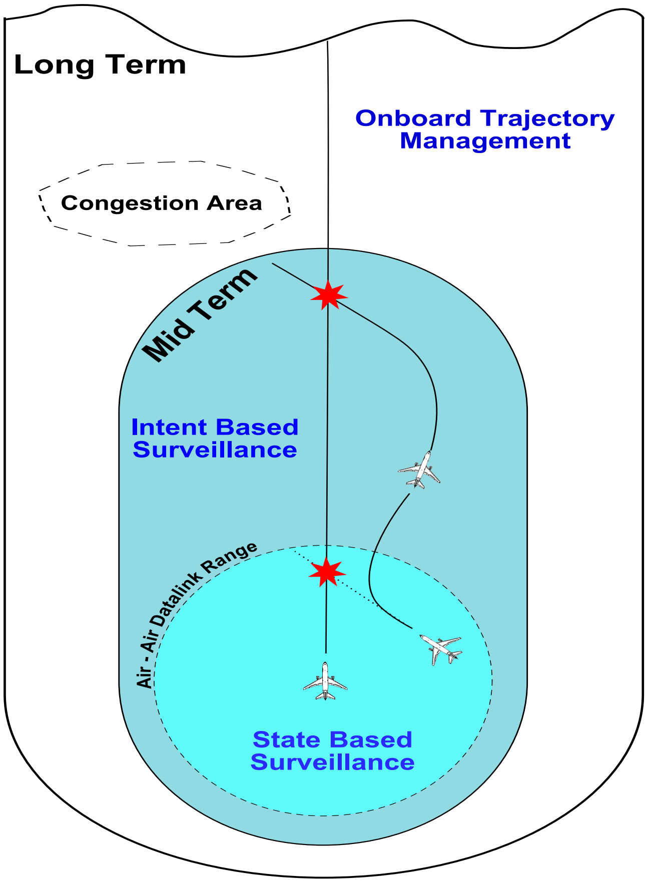

Figure 1: Different levels of the air traffic surveillance.

As discussed in D5.1, [8], from the decision making point of view, conflict resolution processes can be classified as:

- *Long Term Conflict Resolution*, which is related to the flow or trajectory management. This affects the design of the intended flight plan and does not consider individual conflicts but rather the general hazards such as congestion areas, weather, etc. Long term CR includes several hours of horizon and looks beyond local areas of conflict.
- *Medium Short Term Conflict Resolution*, which is the higher level of the Separation Management where individual conflicts with other aircraft are considered for a horizon under consideration of the order of tens of minutes.
- *Short Term Conflict Resolution*, which is the lower level of the Separation Management where individual conflicts with other aircraft are considered

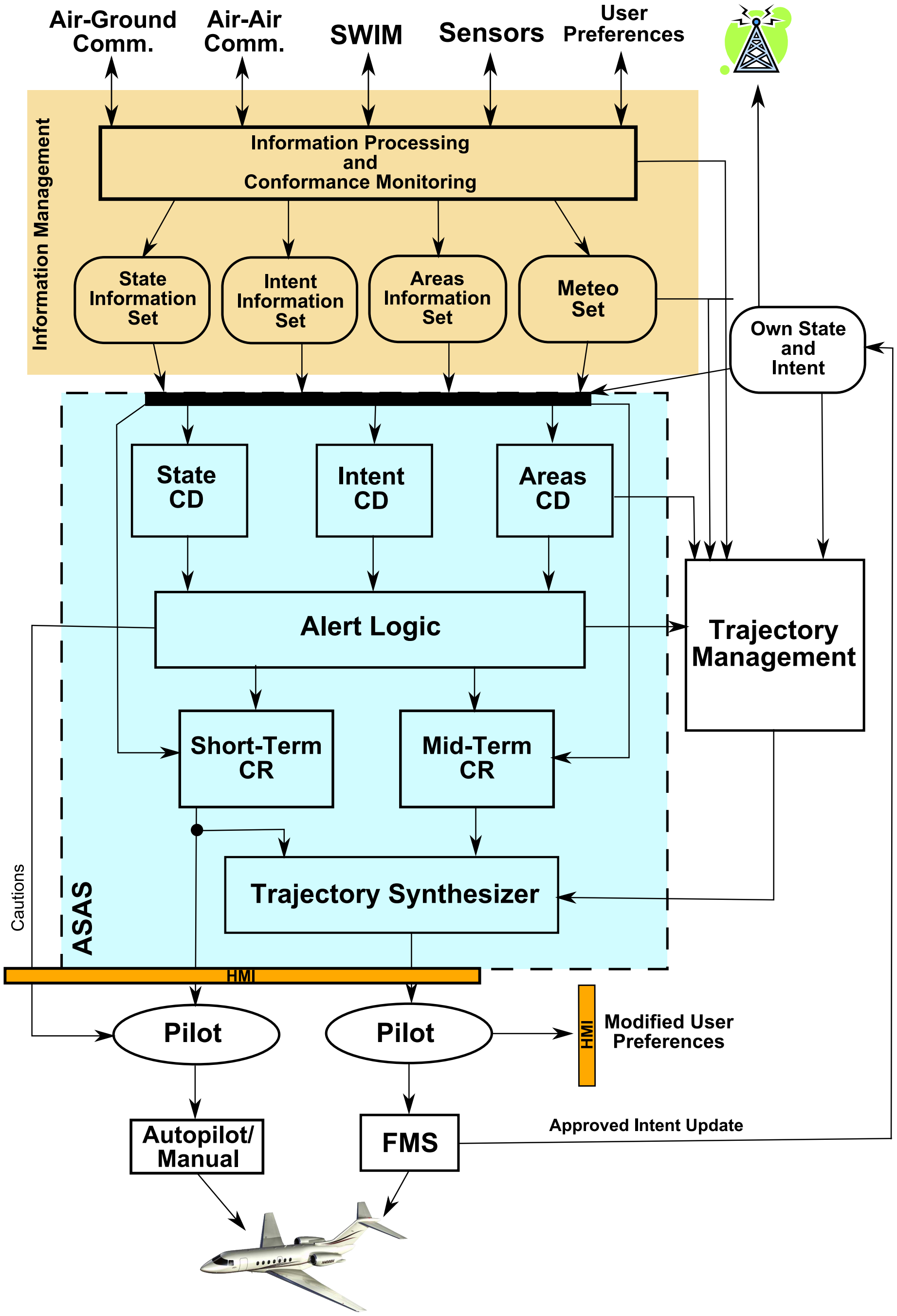

Figure 2: Functional architecture overview of the A^3 airborne separation and trajectory management system (Figure 9.3 on the page 61 of [11]).

for a horizon under consideration of the order of a few minutes.

Moreover, similarly to CD, we can further classify CR methods according to which type of surveillance information is used to perform the conflict resolution:

- **Areas Conflict Resolution** performs the long term resolution (more than 30 minutes) between own RBT and areas-to-avoid provided by other systems (e.g., weather radar), or uploaded from ground.
- **Intent Conflict Resolution** performs the conflict resolution based on the intent-based TP.
- **State Conflict Resolution** performs the conflict resolution based on the state-based TP.

In some sense these two classification types are parallel. One could take this further by suggesting that Areas, Intent and State based CR is most suitable for Long, Mid and Short term CR respectively. On the other hand, it is not necessary that this should be the case. For example, when navigation functions are used for short term CR, each aircraft uses both state information as well as knowledge of other aircraft's goals. Therefore, it is a method that combines both state and intent information. So we shall not restrict to the case where Long, Mid and Short term CR is only Areas, Intent and State based CR respectively, so that one could allow for the case of some reasonable combination of information.

The availability of updated traffic information is a basic enabler of any CR related application. As far as the technologies involved are concerned, information for shorter distances can be provided through direct Air-Air data link communication via Automatic Dependent Surveillance Broadcast/Contract (ADS-B). The information about a flight will be broadcast through ADS-B in the form of different messages: state messages with high update frequency, and intent messages with lower update rates. When the range of ADS-B channels is exceeded, information sharing can be largely provided by the System Wide Information Management (SWIM). SWIM is a communication architecture that is planned to allow the exchange of data across the whole European ATM system by the integration of Air-Ground and Ground-Ground data and ATM services exchange.

2.4 A^3 Requirements for Long Term Conflict Resolution, Flow and Trajectory Management

The Conflict Resolution (CR) applications can be split to two main groups. While the long term CR emphasises on the performance (global in the case of flow management, and performance of own flight within the trajectory management), the mid and short term CR focuses mainly on the own aircraft safety. However, some optimisation aspects are also taken into account in the mid-term level.

An aircraft entering the PBA has always a valid RBT agreed with the ground-based Strategic Flow Management. However, when flying under Autonomous Flight Rules aircrew can modify the autonomous part of this RBT (while satisfying the corresponding exit condition) without renegotiation with ground ATM (changes of the exit conditions still requires a negotiation with the ground). This additional flexibility (with respect to the managed airspace) offers to the user new possibilities to increase flight efficiency.

2.4.1 Ground Based Long Term CR - Strategic Flow Management

Although this application is out of scope of A^3 it provides some important inputs to the autonomous part of a flight. The main part of the process takes place before the take-off and its primary goal is to maximise the overall performance and safety of the global ATM system. This centralised ground-based application is based on the Collaborative Decision Making between involved actors and its main outputs are initial RBTs for all aircraft. From the A^3 point of view, it provides two important inputs to the autonomous flight:

- Initial RBT that an aircraft is flying when entering PBA.
- PBA exit constraint (exit point and related Controlled Time of Arrival).

2.4.2 Airborne Long Term CR - Trajectory Management

The effectiveness of each flight is a key factor for airspace users, in particular airlines. The flexibility of RBT changes within the PBA and the availability of updated information, in particular about the weather, provides a powerful framework for dynamic onboard trajectory optimisation. Within A^3 this task is assigned to the Trajectory Management module. Except purely performance oriented aims, this module is also triggered when some conflict with areas-to-avoid is detected beyond the mid term time horizon.

2.5 A^3 Requirements for Mid and Short term Conflict Resolution within ASAS

Within A^3, the solution(s) of all conflicts within the Mid term time horizon except the conflicts within the ACAS operational time range, is provided by ASAS systems including a crossing of some area-to-avoid. Nevertheless, the ASAS internal CR process must reflect how the provided manoeuvre will be executed. In fact, a provided solution(s) is first assessed by the pilot, accepted or potentially modified, and then executed. This requires some **execution delay time** that must be already included in the proposed manoeuvre and therefore considered by the CR algorithm. Obviously, a safe delay of the CR execution differs for the conflicts 15 minutes ahead and conflicts with only 3 minutes of time-to-conflict. For these reasons there are two CR modules with different execution delay time limits considered in the A^3 concept: Mid term CR and Short term CR.

Very often this splitting of CR process is aligned with the division of the CD process. While A^3 allows this kind of logic, it does not restrict algorithm developers to it. From the system perspective, the only connection between the CD modules and CR algorithms is that a CR algorithm must be able to process trajectory information used by the CD module for detection of the conflict that must be solved, which consists of typically state and/or intent information. While the CD is divided according the type of TP, the splitting of the CR process is based on the urgency of the conflicts, i.e. the choice of the appropriate CR module by the Alert Logic will be given based on the time-to-conflict (and some additional aspects) independently if it was detected by Intent CD or State CD (that are running in parallel, i.e., it is for example possible to detect intent conflict with time-to-conflict of only 3 minutes). In addition, the prevention of secondary conflicts will be more effective if the best available information (whatever it is state, intent, or some their combination) about surrounding aircraft is used within CR algorithm both for Short term and Mid term CR. In conclusion, A^3 allows that the boundary between Mid Term CR and Short Term CR is designed independently of the CD process if the available algorithms support this possibility.

2.5.1 Mid Term Conflict Resolution

Mid term CR should be the main way to solve conflicts with the short term CR playing the role of a backup system. It is possible to assume longer execution delays estimated to be about 2 minutes, which corresponds to the time used by the pilot to understand the situation, assess proposed solutions, select one solution and implement it through the FMS. At the same time it should allow to consider more optimisation and safety aspects and take into account the strategic flow constraints, namely, the PBA exit conditions. The provided solution should be in the form of a complete RBT update that can be directly loaded to the Flight Management System (FMS). This allows an optimised trajectory execution using advanced FMS performance functions (existing or expected to be available at the timeframe of the self-separation deployment). Typically more than one solution could be provided to the pilot (subject of Human Factor (HF) studies), potentially with some suggested classification (e.g., performance-based). As the CR related situation awareness and proposed trajectory modifications can be relatively complex, longer execution delay time is necessary for the pilot to analyse the situation and to make a decision about RBT update acceptance.

It is required that a proposed CR solution will be conflict free for all aircraft within the Mid-term time horizon. At the same time all areas-to-avoid will be avoided (if possible).

2.5.2 Short Term Conflict Resolution

Short term CR should function as a first safety net of Mid term CR with Aircraft Collision Avoidance System (ACAS) being the second one. It must be based on shorter execution delays estimated to be about 30 seconds, the time taken by the pilot to understand the situation and the proposed solutions, to select one and start its implementation. The solution is provided in form of an isolated CR manoeuvre(s) that can be simply interpreted by pilot. The manoeuvre execution will be performed using flight mode panel or manually. More than one solution can be suggested to the pilot but this will be a subject of HF studies. Immediately after the start of the manoeuvre execution, the system will calculate the follow-up update of the RBT and check whether the flight objectives and strategic flow constraints not considered within the Short term CR are satisfied. The Trajectory Synthesiser is responsible for this task.

It is required that a proposed CR solution will be conflict free for all aircraft within the Short-term time horizon. At the same time it is considered that if possible all areas-to-avoid at the same timeframe will be avoided. The coordination with the conflicting aircraft will be implicit (algorithm-based), i.e., no explicit communication will be needed. Due to short time-to-conflict, Short term CR algorithm must be computationally fast and very reliable.

3 Methods for Long Term Conflict Resolution and Recommendations

3.1 Features of Long Term Conflict Resolution Algorithms

As already discussed in D5.1 of iFly, the main features of Long Term Conflict Resolution algorithms can be summarised as following:

- *Safety constraints.* Since the horizons over which these algorithms are resolving potential conflicts are in terms of hours, the safety constraints enter in the algorithms in terms of aircraft densities (e.g. per sector).
- *Global knowledge of intent.* All Long Term CD&R algorithms require knowledge about the (approximate) flight plans of all aircraft in the sector (or a wider area of more than one sectors) for the next hours. In the SESAR context, this is reflected by the RBTs which are globally available.
- *Large computational power.* Since a solution as close as possible to optimality has to be found, while at the same time the uncertainty gaps are very wide, large computational power is needed for the CD&R to find the best solution (with respect also to stakeholder preferences). Of course, since the optimal solution to be found in this level will be computed taking into account large uncertainty gaps, it can permit further Collaborative Decision Making by the stakeholders in the shorter horizons.
- *All other relevant information.* Information like weather forecast, sector capacity constraints, aircraft priorities, airline demands, etc. should also be available to the system.

As previously summarised in D5.1, the algorithms that fall into this category are shown in Table 1.

In D1.1, where the high level A^3 ConOps is described, a different aspect of Long Term Conflict Resolution is also discussed. There, Long Term CR is further divided into:

- Traffic Flow Management (TFM), which corresponds to resolution horizons of more than one hour. This falls into the category of the algorithms reviewed under D5.1 [8].
- Trajectory Management, which corresponds to horizons of up to 1 hour. The goal of this aspect is to generate the optimal path across the Self Separation Air Space, satisfying the existing safety constraints. The key input to this process is the complete flight plan, whose computation may be facilitated by the TFM process. Using updated information about the weather and the hazards in general, this flight plan should be amenable to modifications by the aircraft. This task can also cover a prediction of the congested areas based on the known trajectories of all relevant flights (obtained from onboard systems or ISS). The output of this process can be

Approach Source	SAGHP/ MAGHP/ GTFM	Deterministic/ Stochastic/ Both	Static/ Dynamic/ Both	Optimal/ Heuristic/ Both
[38]	SAGHP	B	B	B
[36]	MAGHP	D	S	O
[35]	MAGHP	S	D	O
[12]	GTFM	D	S	O
[17]	MAGHP	D	S	H
[18]	MAGHP	D	S	H
[27]	MAGHP	D	S	H
[6, 7, 29]	GTFM	D	S	O
[24]	GTFM	D	S	O
[37]	GTFM	D	D	H
[30, 13]	GTFM	S	D	O

Table 1: Summary of Characteristics of Traffic Flow Management algorithms: Single-Airport Ground-Holding Problem (SAGHP); Multi-Airport Ground-Holding Problem (MAGHP); Generalised Traffic Flow Management (GTFM).

in the form of an updated flight plan with additional constraints, e.g., the Required Time of Arrival (RTA) at the Self-Separation Air Space (SSAS) exit point. Based on this optimised flight plan the reference trajectory for the guidance system is generated (and also provided to ISS) by the Flight Management System (FMS).

3.2 Methods for Long Term Conflict Resolution under the A^3 scenario

Since usually the horizons over which the flight path planning takes place are much bigger than typical flight times and some times due to capacity constraints of the system techniques like ground-holding are performed, it is clearly impractical to move functions relevant to TFM on-board aircraft. All the optimisation has to be performed on ground and be transmitted to the aircraft upon availability. So, as far as on-board self separation goes, TFM role is implicit, placing some constraints on the flight plan of the aircraft (which might cover self separation parts of the airspace). Thus, TFM has an important role to play in support of autonomous aircraft. Self separation algorithms will have limitations in terms of the number and density of aircraft they can handle. The role of TFM algorithms should therefore be to ensure that these bounds are not exceeded. We believe that this can be accomplished using existing TFM algorithms, by appropriately setting the capacities of the self separation airspace.

Concerning the Trajectory Management, as defined in D1.1 [20], decentralisation should be possible. This part of the Long Term CR could be implemented by using some of the Mid Term CR tools and algorithms, substituting the required input from the Conflict Detection algorithms with an input from a Congestion Prediction algorithm. The latter should be able to take into account all system updates (such as weather forecast updates), as well as the computed trajectories of other aircraft flying in the SSAS.

For the A^3 concept, we propose to use from the existing TFM methods the ones that allow one to set constraints on sector capacities; the methods of [12, 35, 18, 7, 13] are all adequate for this task. We feel that no further development of these methods will be necessary. The key difficulty will be to determine the parameters to be used by the TFM algorithms (such as sector capacities) for Self Separation airspace. This needs to be done by analysing the short and mid term self separation CD&R algorithms, in order to determine bounds on aircraft densities and other traffic parameters under which they can operate comfortably.

As for the Trajectory Management, we propose to extend the use of Mid Term CR algorithms to longer horizons, solving for congestions instead of conflicts. For this purpose, the extension of Conflict Detection algorithms to efficient Congestion Detection algorithms might also be needed. In the description of the A^3 ConOps in D1.3 [10], a ground-based tool, under the name Complexity Predictor, will inform aircraft about all complex areas detected. The prediction will be based on the RBTs (stored in SWIM), which will be used to evaluate a suitable traffic complexity metric across the airspace. Aircraft will be informed about the Self Separation airspace complexity prior to their flight, and thus, together with the Areas CD algorithm that will be developed for the A^3 scenario (see D1.3 of the project), the TM algorithms will have to properly adjust the RBTs whenever needed onboard.

The methods to be used for solving future congestions should be decentralised. The communication of intent is also important for both the congestion detection as well as the resolution and for finding the best RBT in terms of maximising some objective function of the aircraft. Because of the distributed nature of the algorithms, convergence problems, similar to those described in Section 4 might occur. Section 4 describes some methods to deal with convergence problems of decentralised algorithms of this form. Finally, the algorithms should be able to handle constraints (like areas-to-avoid that will be provided to the aircraft). Fortunately, constraints are easily translated in most Conflict Resolution methods described (and especially the ones proposed) in Section 4. In all cases, the Mid Term CR methods for the Trajectory Management problem should be in line with the operational requirements that the A^3 ConOps has set, as described by D1.3 of the iFly project.

3.3 Initial thoughts on the introduction of A^3 aircraft in the SESAR concept

In the SESAR concept one can envision TFM becoming an integral part of the operations, since this concept also includes a ground component that can provide assistance of the self separation airspace. We propose a similar approach, i.e. to use existing TFM algorithms and set appropriately their inputs and parameters (such as sector capacities) to reflect the limitations of ground supported autonomous aircraft. The application of Trajectory Management techniques can be similar as in the A^3 context, optimising online the aircraft trajectories to avoid possible future congestion due to weather or other aircraft in ASAS. In this case however one can imagine moving the Trajectory Management functionality on ground to remove the need for distributed methods and the convergence problems they may present. Since the parts of the functionalities that will be moved to the ground are not yet decided, our suggestion would be to move the Trajectory Management functionality on ground, as better algorithms exist for a centralised approach in terms of the optimal values found (this fact is also described in Section 4). Then, Trajectory Management should again be addressed by appropriately adjusted Mid Term CR algorithms, as suggested for A^3 aircraft.

3.4 Recommendations

The recommendations for the A^3 concept can be summed up as:

- *Traffic Flow Management :* Use existing TFM methods and incorporate inclusion of capacity constraints in busy areas.
- *Trajectory Management:* Extend the use of Mid Term CR algorithms to longer horizons, solving congestions, instead of conflicts.

In addition, our preliminary investigation into the CR needs/opportunities that arise when ground support is made available to A^3 aircraft under the SESAR concept suggests that:

- *Traffic Flow Management Algorithms:* Use existing TFM methods.
- *Trajectory Management:* Perform centralised optimisation online for aircraft trajectories to avoid possible future congestion.

4 Methods for Mid Term Conflict Resolution and Recommendations

We shall be dealing with the problem of detecting and resolving conflicts that could possibly arise during a so called midterm future horizon time, which should be typically from ten to twenty minutes. We shall assume that longer horizons have been resolved during the Long-term CR level. The ability to compute a reliable prediction of the trajectory of an aircraft on a future horizon of the order of tens of minutes is an essential part of ATM. As discussed in D5.1, [8], in general the classification methods of the prediction models fall into the following categories: deterministic, stochastic and worst case modelling. Conflict resolution methods are further classified according to:

1. Number of Aircraft
    (a) Pairwise Conflicts
    (b) Multi-aircraft conflict
2. Manoeuvre Type
    (a) Turns
    (b) Speed changes
    (c) Altitude changes
    (d) Combination of the above

Using such a classification, we shall attempt first to discuss the operational considerations under A^3 and suggest appropriate methodologies to develop CR algorithm for Mid Term Conflict Resolution.

We consider and propose algorithms that do not only solve the CR problem for a specific scenario, e.g. level cruise only, but instead fit most cases during autonomous flight. This has lead us to believe that optimisation based solutions should be preferred to geometrical approaches or other heuristics. We feel geometrical CR algorithms or certain heuristics are better suited for short-term CR rather than mid-term. In mid-term CR this may lead to considerable loss of optimality and performance. The allocated time for the optimising aircraft at any instant to resolve a potential conflict for the mid-term case might not seem at first as a large amount of time, but certainly is large enough so that initially the decision maker can evaluate and optimise complex cost functions until the end of the decision horizon. Such a generic approach can also benefit from being versatile and compatible with the concepts introduced by other research efforts, such as the SESAR and NextGen concepts of operations.

4.1 Operational Considerations

In this section we have identified all the key operational requirements to be addressed relevant to Mid Term CR as presented in WP1 and WP2, [20] ,[3]. We have to stress that the algorithms to be considered do not fall in the human responsibility within the A^3 concept, but are tools for the optimiser or automated manoeuvre generator, which effectively proposes recommended solutions.

4.1.1 Number of aircraft

Currently there is a need to address the problem of multiple aircraft being in conflict rather than just a pair coming too close. It is important to extend pairwise CR to solve the conflict of the whole cluster of aircraft. A possible approach would be to use an iterative scheme and apply in parallel or cycles pairwise methods. The problem with this is that it is difficult to guarantee stability as the possibility of domino effect between pairwise conflicts can appear.

Naturally we shall opt for resolving for clusters of aircraft that fly in close proximity. We shall assume that groups of aircraft have been already selected to form clusters. Then optimisation can take place for each cluster, without having to account further for each cluster size, as optimisation techniques are flexible to have an arbitrary number of states and control inputs.

4.1.2 Manoeuvre Type

One can perform optimisation based CR by choosing resolution manoeuvres from a subset of standard flight procedures. In Wing, [14], such a restricted optimisation was conducted using genetic algorithms. Such an approach could have two benefits for Conflict Resolution algorithms. First, it would reduce the decision space, hence potentially reduce computational complexity of optimisation-based CR, hence make it more practical. Second, it could make CR more resilient to interruption of communications between aircraft. For example, in marine navigation safe manoeuvring known not to make matters worse in the absence of communications can be found in marine Collision Prevention Regulations with rules such as “All vessels turn to starboard”. In civil aviation such a procedure of safe manoeuvres is provided by TCAS. The same benefit of the reduced decision space applies when manoeuvres are split into horizontal and vertical, considered separately or when priority rules apply.

In terms of formulating an optimisation problem all cases can be dealt with. Any set of initial manoeuvres can be used to create an initial feasible solution and then an adaptive scheme such as Model Predictive Control(MPC) can boost performance and satisfy any additional constraints. On-line optimisation based methods demonstrate a flexibility that allows to pose constraints and further performance criteria once safety has been achieved. Examples may include user preference, complexity of future traffic, fuel restrictions etc.

4.1.3 Decentralised decision making

The use of decentralised decision making is very critical for the A^3 case. In [20], a decentralised approach in decision making assumes that SWIM provides efficient information-sharing and therefore mutual cooperation is possible. Assuming that the communication channels are robust and reliable this is by all means consistent with our approach as each decision maker has available all the necessary parameters to solve a CR problem in a collaborative fashion. In the case of unreliable communication, one could argue geometrical or heuristic approaches seem more attractive, but there is not any justification that these can perform better than decentralised optimisation methods.

Furthermore, it is common to assume that each aircraft needs to receive precise intent information from every other aircraft involved in the cluster in order to determine the Mid Term Awareness Zone. We feel that this can be relaxed even in a decentralised formulation of CR. It is possible to make worst-case computations about other aircraft without knowing precisely their intent. These can be also combined with Monte Carlo (MC) computations as seen in [16]. Of course, this approach may be conservative in densely-populated airspace, but might work well for sparsely-populated en route sectors. In any case an optimisation framework can deal with imprecise intent in both the centralised and decentralised cases by encoding this properly in the cost functions and/or posing additional constraints.

4.2 Methods for Mid-term resolution under the A^3 scenario

Under the A3 scenario, the ground can be seen as a communication resource only, but cannot contribute to the decision-making involved in conflict resolution.

This causes the A3 concept to pose the biggest challenges to conflict resolution algorithms, for two reasons:

1. The absence of a natural central authority implies that the participating aircraft should either share the decision-making task between them, or agree to delegate the task to one of the aircraft and subsequently accept that aircraft's decisions and directives.

2. The ground could be assumed to have arbitrarily large computing resources available to it, whereas on-board computational resources are likely to be a limiting factor.

Deterministic (non-stochastic) algorithms should be investigated for mid-term conflict resolution in the A^3 context, even though the actual aircraft locations and trajectories are strongly influenced by stochastic phenomena. Also, suggesting that not to consider any sort of stochastic optimisation algorithms for the A^3 concept is mainly because of the computational power required by most of these methods would prohibit on board implementation. Of course, the use of deterministic algorithms does not preclude the use of stochastic tools to evaluate their performance.

We assume here that CR is to be solved cooperatively by the participating aircraft, sharing the computational task between them. We therefore consider algorithms for *decentralised control*. The central problem in decentralised control is to ensure that the partial solutions proposed and acted upon by each agent (aircraft) are consistent with each other and lead to successful resolution of conflicts. The main advantages of distributing the computation between the participating agents are that the computational requirement on each one is reduced, and scales benignly as the number of participating agents increases.

We start our investigation of possible mid term CR algorithms for the A^3 concept by considering the following candidate algorithms: *Robust decentralised model predictive control* proposed by Richards and How [4], robust decentralised model predictive control using *tubes* proposed by Trodden and Richards [34], and robust *multiplexed* model predictive control proposed by Richards et al [5]. Many other algorithms have been proposed for decentralised control, but the majority of them assume that the dynamics of the agents are cross-coupled, and they achieve consistency between agents by adjustable cost functions which are coordinated by some 'price-adjusting' mechanism. The algorithms selected here are particularly well suited to the case that the agents' dynamics are independent of each other, with all the coupling arising from constraints between the agents. This is precisely the situation in conflict resolution, in which the coupling constraints are the minimum-separation requirements.

All three selected algorithms assume that disturbances (principally wind in the conflict resolution scenario) have bounded magnitudes, but their probability distribution information is not incorporated in the algorithm. In reality, the disturbances present are stochastic and are usually modelled as Gaussian distributions which are unbounded. For application of the algorithms considered, it is necessary to appropriately identify approximating disturbance bounds which would achieve suitably low probabilities of conflict. The magnitudes of the chosen bounds are required to be suitably low to ensure the problem is not unnecessarily conservative, and that solutions exist.

In all three of the algorithms selected above, conflict resolution manoeuvres are found by optimising a utility (or cost) function so as to retain desirable objectives, such as minimising deviations from a set of flight plans, while strictly avoiding violation of constraints, such as minimum separation constraints. In [4] each agent (aircraft) plans its own trajectory over some future horizon (tens of minutes in the mid-term CD&R context) by solving a small part of the overall optimisation problem that relates to itself. Each aircraft communicates its own future plans to all the other aircraft potentially involved in the conflict. The constraints which appear in the optimisation problem solved by each aircraft are tighter than the actual separation requirements, in order to allow for the effects of future disturbances on aircraft trajectories, and for the fact that incomplete information is available to each agent about the other agents' future plans. The details of the constraint tightening, and of the problem formulation, are adjusted (offline, at the algorithm design stage) such that the algorithm has the following property:

> *If a successful set of resolution manoeuvres is found when a conflict is first detected, then a successful set of resolution manoeuvres will continue to exist until the conflict has been resolved.*

That is, the algorithm is guaranteed not to 'paint itself into a corner' from which there is no escape. There is no free lunch, however, and the catch is that the algorithm may not find a successful set of manoeuvres when a conflict is first detected. The likelihood of this is much reduced by detecting conflicts sufficiently early.

The algorithm proposed in [5] combines the ideas of [4] with those of [25]. [4] assumes inter-agent communication as each agent solves its own sub-problem, followed by simultaneous implementation of the solution by each agent when all the sub-problems have been solved. On the other hand, in [5] it is assumed that each agent solves its own sub-problem, then implements its solution and communicates its future plans to the other agents. The solution and implementation is thus foreseen to take place one agent at a time, cycling around all the agents. This seems to be much more natural in the ATM context, and it is likely to have benefits (hitherto not investigated) as regards resilience to temporary communication failures. The algorithm retains the performance guarantee offered by [4] (with the same caveat).

The proposal in [34] is similar to that in [5], in that it also envisages solution and implementation by one agent at a time, with communication of future plans to all other participating agents. The difference is largely one of technical details. In [34] the shape of a 'tube' is defined offline, during algorithm design, which is such that each agent can be guaranteed to be able to remain inside the tube, given only the 'centre' of the tube at each time. The online problem to be solved then consists of planning the future trajectory of centres of each tube, over some horizon. Again the problem is set up in such a way that if each agent solves for its own planned trajectory, and communicates its plans to the others, then successful conflict resolution can be guaranteed, providing that a solution is found initially, when the conflict is detected.

A closely-related proposal which should also be considered is that in [39]. This relies on mixed-integer optimisation, however, and therefore involves high computational complexity.

4.3 Initial thoughts on introducing A^3 aircraft in the SESAR concept

We envision that the algorithms selected for use in the A^3 can provide reliable solutions sufficiently quickly. These distributed solutions can also be used as the starting point for conflict resolution when ground support is also available. But the possibility exists of improving them, by taking advantage of the central decision-making capability of the ground, acting as a 'master agent'. Thus a kind of *policy iteration* scheme is envisaged, in which the A^3 algorithms provide an initial proposal to be improved in later research. One possibility is that the A^3 algorithms prove to be sufficient for constant-altitude resolutions (typically en-route), but that more powerful ground based algorithms will be needed for resolutions that involve altitude changes (typically in a Terminal Manoeuvring Area (TMA) context).

Such powerful algorithms can be found in the stochastic analysis and modelling areas. The use of applied probability and statistical modelling can provide a very general way of handling uncertainty by probability density functions. This uncertainty can be due to the effect of the wind motion, atmospheric pressure or terrain effects on the aircraft dynamics. Stochastic modelling has certain advantages over many deterministic approaches detailed in D5.1, [8]. In addition, recent studies in [16] have shown how a probabilistic approach can be effectively combined in some cases of interest with worst case modelling.

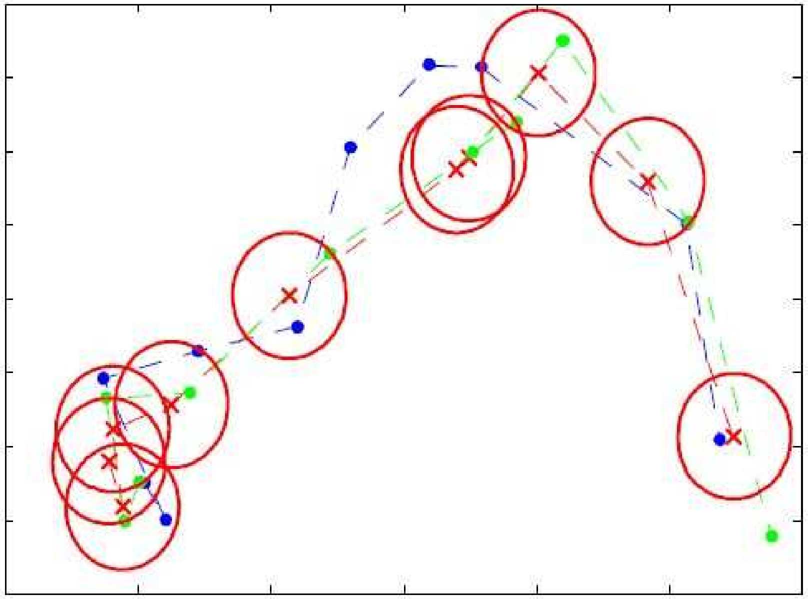

Figure 3: Aircraft Motion Modelling using probability distributions. Blue points indicate intent position, green points are current state, red crosses is conditional mean and conditional covariance are given by red ellipse.

In [40] a model was proposed to capture the motion of any aircraft as a stochastic hybrid system using continuous time, where the randomness of the model is due to the wind applying random forces. Since the state of the aircraft is periodically monitored by radar, it makes sense to discretise any continuous time model to obtain a discrete time one. Therefore, in discrete time the state of the aircraft can be modelled as a sequence or flow of probability distributions. An example is shown in Figure 3 where the two dimensional state of the aircraft is modelled by a sequence of distributions updated in a Bayesian setting given its own intent information and radar observations. Note that this is a very simplified example for illustration purposes only and more accurate modelling is available using sophisticated Monte Carlo simulations as in [40]. The authors feel that incorporating discrete mass approximations of the distribution sequence using Sequential Monte Carlo (SMC) simulation, also known as particle filters, can lead to impressive accuracy without making any restrictive assumptions on the kinematic models, such as linearity or gaussian distributions as in the popular Kalman filter. These methods are suitable for general state spaces and nonlinear and non-gaussian dynamics and have proven extremely successful in many areas of statistical computing, such as finance, robotics, communications etc, [1].

Moreover without further modelling restrictions, we can effectively reduce the motion of an aircraft to a discrete time controlled Markov chain, where the control or action parameters are integrated in the aircraft Flight Management System (FMS) or autopilot system. These control inputs have to optimise an objective given by an expectation of a nonlinear function. The main difficulty in maximising such an objective is that such an expectation might not be analytically tractable, so one has to resort to numerical approximations. The most successful approaches in the statistical computing literature are mainly Markov Chain Monte Carlo (MCMC), see [9], and Sequential Monte Carlo (SMC), see [1, 31]. Therefore, Monte Carlo simulation can provide a very powerful tool both for the aircraft motion prediction model as well as the difficult optimisation involved. A MCMC technique developed in [32] was used in [28] for a pairwise CR problem when two aircraft descent to a Terminal Manoeuvring Area.

It is important to develop methods of recursively update these controls in a sequential setting, as this would enable the use of intelligent control methods as well, such as Model Predictive control (MPC). This methodology benefits from an intuitive control law implementation using a receding horizon strategy whilst enabling the user to verify stability and optimality issues via a plethora of analytical tools. For more details on these methods we refer the reader to [26]. Similar successful alternatives can be Open loop or Closed loop Feedback control (OLFC, CLFC),[15].

Another nice feature of the stochastic optimisation methods that we propose to use (and already promoted by HYBRIDGE) is that the decision-maker is presented with a “probability cloud” of safe decisions, and can pick one from this cloud (see example in Appendix). Apparently this has also been utilised in [23] for Mediterranean Free Flight (MFF), where the pilot can choose between only two, horizontal or vertical manoeuvres. An interesting topic relevant to assessing which choice out of a set of safe manoeuvres should be made involves minimising the *Predicted Complexity*, which is essentially choosing resolution manoeuvres that cause the lowest increase in complexity. This can greatly relieve the computational burden of ATM. If this needs to be adopted, this would require input from WP3 into WP5, as WP3 is concerned with evaluation and prediction of complexity of the airspace. This topic is still under research and will be considered when deriving an analytical solution for CR.

To allow on line implementation, the authors feel that although Monte Carlo techniques are intuitive and conceptually easy to understand, they cannot be used in crude or “black box” manner and require a significant amount of expertise. Any naive implementation strategy will cause the computation to be completely inefficient. Much care has to be taken so that the computation takes advantage of the system’s dynamics and use more efficient advanced methods found in [1]. Finally for the special case of Sequential Monte Carlo, we have to stress that the computation can be always parallelised, [2], making them increasingly more appealing for applications when implemented on standard GPUs.

4.4 Recommendations

We sum up briefly our recommendations:

- A^3 **aircraft:** A deterministic *Decentralised, Robust MPC* approach is recommended.
- **Autonomous aircraft in the SESAR concept:** An approach of using stochastic control combined with advanced Monte Carlo methods is recommended. The resulting algorithm can be possibly seeded with the decentralised A^3 solution. Finally, a randomised feedback policy based on MPC can be implemented using SMC or MCMC.

The main reason for preferring a deterministic optimisation scheme for the A^3 concept is due to the limited computational capabilities that can be transferred on board. As this is not necessary when ground support is available, in that case we opted for a Monte Carlo approach instead. Furthermore, the theoretical guarantees provided in the *Decentralised, Robust MPC* method make this more attractive for safety critical applications than most distributed stochastic algorithms. This is not the case when ground support is available, because in a centralised optimisation problem safety constraints are guaranteed to be obeyed in both cases. In this case, the main advantage of Monte Carlo methods is that they can compute optimal solutions for problems that are analytically intractable without having to resort to crude approximations.

5 Methods for Short Term Conflict Resolution and recommendations

Short-term CD&R operations in the iFLY project, as defined in D1.1, refer to conflicts that are up to about 5 to 6 minutes of flight time away. These conflicts should be handled primarily by the Airborne Separation Assurance System (ASAS), while some form of Aircraft Collision Avoidance System (ACAS) must also be present in order to prevent conflicts that are less than 1 minute away and could lead to a midair collision. It is important to note though that the ACAS system is an emergency measure and it should not be relied upon to ensure separation between neighbouring aircraft when designing the ASAS system. Nonetheless, since the Short-Term ASAS and the ACAS systems will eventually co-exist, it is necessary that they can operate simultaneously, with the ACAS monitoring the ASAS operations and overriding it only when it is required. Therefore the interface between ASAS and ACAS must be considered and the ASAS must be designed to resolve conflicts before the ACAS system is triggered.

Based on the the Concept of Operations described in D1.1 [20] of iFly, a number of requirements arise for short-term CD&R methods. First of all, as stated above and explained in D5.1, the short-term CD&R strategy must offer guaranteed performance so that flight safety is assured. Specifically, short-term ASAS operations ought to be enough to guarantee conflict resolution without the need of an ACAS system (like TCAS) so that there is some form of redundancy to ensure safety. Of course the resolution manoeuvre proposed by ASAS must be feasible, i.e. comply with the kinematic and dynamic limitations of the aircraft. Furthermore it is generally accepted that short-term CD&R must be performed on-board, in a decentralised manner, in contrast to longer horizon operations which are more suitable for implementation on the ground. This however does not by any way imply that ground controllers and systems, like STCA (Short Term Collision Alert), cannot facilitate the short-term decision making by providing information (traffic, weather, etc) through a central system like ISS, as described in the concept of operations.

5.1 Conflict Prediction

The detection and efficient resolution of conflicts in the Short Term level will be probably achieved by exploiting primarily state information from surveillance and intent information of the own aircraft based on the current currently planned trajectory. Intent information of neighbouring aircraft communicated through ADS-B or ISS in the future may be used as well, though it should not be required for the safe operation of the short-term ASAS. Although intent information can be very valuable for the reliable prediction and efficient (in terms of fuel consumption, delay, passenger comfort, etc) resolution of conflicts in the mid-term level, it is less important in short-term CD&R where optimality is not as important as safety. For the short-term CD&R level, a deterministic model is considered adequate as the 5-6 minutes interval is not long enough for errors caused by uncertainties to build up more than what can be taken into account by increasing the safety margins.

Specifically, for the detection of conflicts two methods are discussed: trajectory intersections and Alert Zone (AZ). The former method performs an extrapolation of own and neighbouring aircraft trajectory in the future and checks for any loss of separation. In this approach intent information is useful for long term predictions, although for a time horizon of a few minutes state based prediction is usable. Conflict detection using an alert zone is performed by continuously monitoring a certain volume around the own aircraft for intruders. Any penetration of this volume triggers the ASAS system to perform conflict resolution. The choice of the alert zone is of great importance for this method as its shape and size must take into account the speed and manoeuvrability of the aircraft, so that a safe resolution manoeuvre can be performed in time while still avoiding unnecessary alerts and reduction in airspace capacity. Moreover its shape must be simple enough to facilitate the detection of any intruding aircraft, while its size can be defined either in straight line distance or in time-to-conflict. It should be noted here that the ACAS and ASAS system do not necessarily share this detection criterion, as ACAS detects actual collisions in the near future instead of conflicts.

5.2 Conflict Resolution - Constraint Handling

Aircraft (especially civil ones) are faced with a number of mechanical and aerodynamic constraints that limit their ability to perform manoeuvres. These limitations must be taken into account for the generation of the resolution manoeuvres so that they can be performed by the aircraft. In the horizontal plane constraints apply in general to the longitudinal velocity of the aircraft (lower and upper bound), maximum acceleration and turn rate. For vertical (or fully 3D) manoeuvres additional constraints on the climb rate, the flight path angle and the angle of attack need to be considered. Constraint handling is especially important in the Short-Term CD&R level because of the relatively small lookahead time resulting in demanding manoeuvres. manoeuvres in the mid-term level are in general smoother, while any deviation caused by the aircraft's limited manoeuvreability can be handled by the short-term level.

The above constraints in practice limit the manoeuvreability of the aircraft and hence their ability to steer away from collision. The bounds on the velocity in particular are especially important in high altitude cruising where the feasible velocities lie within very narrow bounds. The limited manoeuvreability can lead to situations where a conflict has not yet occurred, but is unavoidable by the engaging aircraft. Therefore the CD&R system must be able to detect dangerous situations and respond soon enough so that all conflicts are avoided despite the limited manoeuvreing capabilities.

5.3 Methods for Short Term CD&R under the A^3 Scenario

The existing TCAS system that has been presented in D5.1 is intended for the role of ACAS, i.e. an extra safety measure designed to prevent a mid-air collision even when a conflict has occurred. In its present form, TCAS uses criteria like the time-to-conflict, as estimated by the current state, to trigger the resolution procedure. It can coordinate the resolution manoeuvres between conflicting aircraft and includes multi-threat logic to handle more than one intruders.

As has been mentioned before short-term ASAS has certain requirements (safety, fast response, small horizon) that make decentralised methods more suitable than centralised ones. In D5.1 the main competing candidate solutions for the ASAS operations were found to be optimisation methods and Potential Field methods such as Navigation Functions. As it has been explained in detail in D5.1, probabilistic optimisation techniques cannot in general guarantee conflict-free performance, while inherent computational issues and combinatorial complexity are difficult to overcome. These issues are especially difficult to resolve in situations involving more than 2 aircraft, which will be getting more often in the years to come, as airspace density and traffic complexity increase. Game theoretic, worst case approaches on the other hand are far too conservative and can quickly reach an infeasible situation where no solution can be provided. In contrast CD&R using decentralised Navigation Functions (NFs) can guarantee flight safety (assuming a deterministic kinematic aircraft model) while keeping the computational workload under control. The methodology has been already applied to multiple, nonholonomic agents, while the extension to 3D vehicles is in progress [22, 33]. One especially important characteristic of the NF method is that no explicit communication is required, as the implicit coordination built into the algorithm is enough for safety. Constraint handling is not as straight forward as in optimisation methods and requires further research. An efficient combination of underlying Navigation Function-based control with an overseeing Model Predictive Controller (MPC) using optimisation techniques is under research [21, 19]. Such an approach could offer the best of both worlds, as safety is guaranteed by the use of Navigation Functions in the short-term level, while the MPC handles manoeuvre feasibility and optimality by setting appropriately the reference target for the Navigation Functions.

Further development of the Navigation Functions methodology towards better handling of constraints is in progress while another approach that inherently takes constraints into account is currently under development in NTUA.

In conclusion the Short-Term CD&R problem is expected to find a solution by some use of Navigation Functions, though further research is required. It should be noted that the presence of kinematic and dynamic constraints makes the resolution of an arbitrary traffic conflict scenario very difficult, if not impossible. Therefore the limits of the short-term method must be estimated (in terms of traffic density, complexity or other suitable measure). Although short-term CD&R is the last resort for separation management and thus it must assure safety, the interface with the higher levels and especially mid-term must be taken into account; after all the short-term level must be able to resolve only those situations that ”escape” from the mid-term level. Therefore it seems that the combination of short-term and mid-term systems can offer safe CD&R for cases which system separately cannot resolve.

5.4 Initial thoughts on introducing A^3 aircraft in the SESAR concept

As explained above, decentralised algorithms are preferred for Short-Term CD&R. This still holds when ground support is available, since centralised decision making is intended to be included in the Mid-Term and Long-Term CD&R levels. Decentralised approaches do not rely on communication with conflicting aircraft or a central authority and therefore can operate even during communication loss. Thus the recommendation for Short-Term CD&R methods under SESAR operation is no different than the one for the A^3 concept. The addition of centralised control in the Mid and Long-Term CD&R levels (where it is more suited and beneficial) should in general also improve the performance of short term CR methods. Considering that, it is most probable that the Short-Term CD&R algorithm used in the A^3 concept will be more than enough for A^3 aircraft in a SESAR context, as the higher CD&R will now be more effective in resolving conflicts before reaching the Short-term level.

5.5 Situation Awareness and Human Factors

In order to facilitate the transition to more automated onboard CD&R, the pilot should maintain some level of control over the way the resolution manoeuvres are calculated; the type of the manoeuvre (vertical only, horizontal only, full 3D) should be selectable when this is possible. If more than one conflict-free manoeuvres are feasible, pilot preference and local ATC service provider guidelines should be taken into account for the final choice. The ability to select the most appropriate manoeuvre between a number of (non-trivially different) suggestions by the ASAS system, when this is possible, may be preferable, though this is subject to HF studies; the proposed manoeuvres may be too deep and complex for the crew to comprehend, at least within some sensible time, so that the manoeuvres remain valid. It is also probable than in dense situations there will be little room for human choice in order to ensure conflict resolution, as only a single manoeuvre may be possible. Moreover the ASAS system should offer adequate Situation Awareness (SA) to the onboard crew so that they have overall control of the procedures and are alerted in advance of any possible conflicts so that they can anticipate the resolution manoeuvres required. To address all these issues more effectively ,WP5 is collaborating with WP2 within the iFly project. Remaining progress will be reported in Deliverable D5.3.

5.6 Recommendations

The recommendations for the Short Term CR in the A^3 concept can be summed up as:

- Use Navigation Functions combined with MPC to handle manoeuvre feasibility and optimality.

In addition, our preliminary investigation into the CR needs/opportunities that arise when ground support is made available to A^3 aircraft under the SESAR concept suggests that:

- Use Navigation Functions combined with MPC.

6 Conclusions and summary of recommendations

In this report we have identified the operational requirements for conflict resolution in Air Traffic Management (ATM). These requirements were presented in such a way that a framework was established, enabling us to suggest different strategies and algorithms to perform CR under the A^3 concept of operations.

The study was divided in three main parts depending on the time horizon involved, namely Long-, Mid- and Short term Conflict resolution. The specific nature of the problem in each case makes it necessary to accept different kinds of requirements and pose different assumptions. This might potentially lead to different adoptions in methodology and implementation for each case. We have to stress here that this is not an issue as each problem needs to be solved in completely different scenarios, which are clearly decomposed according to the ATM structure without any clash.

The recommendations for the A^3 concept can be summed up as:

- **Long term CR**
  - *Traffic Flow Management Algorithms:* Use existing TFM methods allow setting constraints on sector capacities.
  - *Trajectory Management:* Extend the use of Mid Term CR algorithms to longer horizons, solving online congestions, instead of conflicts.
- **Mid term CR:** Use of deterministic Decentralised, Robust MPC.
- **Short term CR:** Use Navigation Functions combined with MPC to handle manoeuver feasibility and optimality.

In addition, our preliminary investigation into the CR needs/opportunities that arise when ground support is made available to A^3 aircraft under the SESAR concept suggests that:

- **Long term CR:**
  - *Traffic Flow Management Algorithms:* Use existing TFM methods.
  - *Trajectory Management:* Perform centralised optimisation online so that the aircraft trajectories to avoid possible future congestion.
- **Mid term CR:** Use stochastic control with feedback combined with Monte Carlo.
- **Short term CR:**Use Navigation Functions combined with MPC.

So far we have not identified any problems with the concepts or the proposed solutions. All the recommendations have been developed well in the literature and have been proven successful. Of course, there is work needed to be done to further develop and implement the algorithms proposed for Mid and Short term CR, so that they adapt to the A^3 concept of operation. This has been foreseen in the statement of work as Task 5.3. More specifically, for the mid term CR the work that follows will mainly focus on developing Decentralised, Robust MPC algorithms for the A^3 concept. We will also conduct a preliminary investigation into the possibility of using more advanced SMC or MCMC algorithms for stochastic MPC, with a view toward introducing A^3 aircraft in the SESAR concept. For the short term CR, 3D Navigation functions with input constraints are being developed for the A^3 concept. We will also conduct a preliminary investigation into the use of navigation functions combined with MPC for A^3 operations under SESAR support.

Finally, progress in WP5 has been relatively smooth, and we do not anticipate any delays, or knock-on effects on other work packages or the overall iFly work flow. A common concern for all CR approaches is how to efficiently deal with the large amount of computational requirements. Furthermore, theoretical guarantees for some of the algorithms might emphasise their capabilities and serve as an important element for validation. It is the view of the authors that in parallel to implementation of advanced algorithms to support the A^3 concept (some of which have been developed in HYBRIDGE), fundamental research on the methodology and framework should continue to be carried out, as it might promise a large reduction on the computational burden as well. Finally, as described earlier a closer collaboration with WP7 and WP3 can be established to address issues like conflict detection or prediction of complexity respectively. Much of WP3 and WP7 findings can be valuable inputs for the success of WP5.

References

[1] Doucet A., De Freitas J.F.G., and Gordon N.J. *Sequential Monte Carlo methods in practice.* Springer Verlag, New York, 2001.

[2] Lee A., Yau C., Giles M., Doucet A., and Holmes C. On the utility of graphics cards to perform massively parallel simulation with advanced monte carlo methods. Technical Report arXiv:0905.2441v3, 2009.

[3] Luuk A., Wise J.A., Pouw F., and Gauthereau V. Description of airborne human responsibilities in autonomous aircraft operations. iFly Deliverable D2.1, 2007.

[4] Richards A. and How J. A decentralized algorithm for robust constrained model predictive control. In *Proc. American Control Conference*, Boston, MA, June 2004.

[5] Richards A., Ling K.V., and Maciejowski J.M. Robust multiplexed model predictive control. In *Proc. European Control Conference*, Kos, Greece, July 2007.

[6] E. Boyd, R. Burlingame, and K. Lindsay. An algorithm for the management of national air traffic. Technical Report INEN/OR/WP/10/5-94, Texas A&M University, Texas, USA, 1994.

[7] R. Burlingame, E. Boyd, and K. Lindsay. *Solving Large Integer Programs Arising from Air Traffic Flow Problems*, pages 215–226. Kluwer Academic Publishers, Boston, MA, 1995.

[8] Roussos I.P. Kyriakopoylos K. Siva E. Lecchini-Visintini A. Maciejowski J.M. Casek P. Chaloulos G., Lygeros J. Comparative study of conflict resolution methods. *iFly Deliverable D5.1*, 2008.

[9] Robert C.P. and Casella G. *Monte Carlo Statistical Methods.* Springer Verlag, New York, 2004.

[10] G. Cuevas, I. Echegoyen, J.G. García, P. Cásek, C. Keinrath, F. Bussink, and A. Luuk. Autonomous aircraft advanced (A^3) conops. *iFly Deliverable D1.3*, 2008.

[11] Garcia J.G. Casek P. Keinrath C. Bussink F. Luuk A. Cuevas G., Echegoyen I. Autonomous aircraft advanced (a3) conops. *iFly Deliverable D1.3*, 2008.

[12] Bertsimas D. and Patterson S. The air traffic flow management problem with enroute capacities. *Operations Research*, 46:406–422, 1998.

[13] A. d'Aspremont, D. Sohier, A. Nilim, L. El Ghaoui, and V. Duong. Optimal path planning for air traffic flow management under stochastic weather and capacity constraints. *International Conference on Research, Innovation and Vision for the Future*, 2006.

[14] Wing D.J. A potentially useful for airborne separation in 4d-trajectory atm operations. *In AIAA 5th Aviation Technology, Integration and Operations Conference, Arlington, VA;*, 2005.

[15] Bertsekas D.P. and Tsitsiklis J.N. *Neuro-Dynamic Programming.* Athena Scientific, Belmont, MA, 1996.

[16] Crisostomi E., Lecchini-Visintini A., and Maciejowski J.M. Combining monte carlo and worst-case methods for trajectory prediction in air traffic control: a case study. *Journal of Guidance, Control and Dynamics, submitted*, 2008.

[17] Andreatta G., Brunetta L., and Guastalla G. Multi-airport ground holding problem: A heuristic approach based on priority rules. *Modeling and Simulation in Air Traffic Management*, pages 71–89, 1997.

[18] Andreatta G., Brunetta L., and Guastalla G. Solving the multi-airport ground holding problem. *Annals of Operations Research*, 81:271–288, 1998.

[19] Chaloulos G., Roussos G. P., Lygeros J., and Kyriakopoulos K. J. Ground assisted conflict resolution in self-separation airspace. *AIAA Guidance, Navigation and Control Conference and Exhibit*, 2008. to appear.

[20] Cuevas G., Rodríguez I., Bordón V., Cásek P., Wise J. A., Keinrath C., Brázdilov á S.L., Kubalčík J., Verbeek R., Luuk A.and Irvine R., Sedaoui A., and Gauthereau V. Autonomous aircraft advanced (a3) high level conops. *iFly Deliverable D1.1*, 2007.

[21] Roussos G.P., Chaloulos G., Kyriakopoulos K. J., and Lygeros J. Control of multiple non-holonomic vehicles under uncertainty using model predictive control and decentralized navigation functions. 47^{th} *IEEE Conference on Decision and Control.*

[22] Roussos G.P. and Kyriakopoulos K. J. 3D navigation and collision avoidance for a non-holonomic vehicle. *2008 American Control Conference, Seattle, Washington, USA*, 2008.

[23] Blom H., Krystul J., Bakker G.J., Klompstra M.B., and Obbink B.K. Free flight collision risk estimation by sequential monte carlo simulation. In Cassandras C.G. and Lygeros J., editors, *Stochastic Hybrid Systems.* CRC Press, 2006.

[24] M. P. Helme. Reducing air traffic delay in a space-time network. In *IEEE International Conference on Systems, Man and Cybernetics*, pages 236–242, Chicago, 1992.

[25] Ling K.V.and Maciejowski J.M. and Wu B.F. Multiplexed model predictive control. In *Proc. IFAC World Congress*, Prague, July 2005.

[26] Maciejowski J.M. *Predictive control with Constraints.* Prentice Hall, 2002.

[27] Navazio L. and Romanin-Jacur G. The multiple connections multi-airport ground holding problem: Models and algorithms. *Transportation Science*, 32(3):268–276, 1998.

[28] A. Lecchini-Visintini, W. Glover, J. Lygeros, and J. M. Maciejowski. Monte Carlo Optimization for Conflict Resolution in Air Traffic Control. *IEEE Transactions on Intelligent Transportation Systems*, 7(4):470–482, 2006.

[29] K. Lindsay, E. Boyd, and R. Burlingame. Traffic flow management modeling with the time assignment model. *Air Traffic Control Quarterly*, 1(3):255–276, 1993.

[30] A. Nilim and L. El Ghaoui. Algorithms for air traffic flow management under stochastic environments. In *American Control Conference*, 2004.

[31] Del Moral P. *Feynman-Kac formulae:genealogical and interacting particle systems with applications.* Springer Verlag, New York, 2004.

[32] Muller P. Simulation based optimal design. *Bayesian Statistics 6*, pages 459–474, 1999.

[33] Roussos G. P., Dimarogonas D.V., and Kyriakopoulos K.J. Decentralized 3D navigation and collision avoidance for multiple nonholonomic agents. 47^{th} *IEEE Conference on Decision and Control.* submitted.

[34] Trodden P.A. and Richards A.G. Robust distributed model predictive control using tubes. In *Proc. American Control Conference*, June 2006.

[35] Vranas P.B.M, Bertsimas D., and Odoni A.R. Dynamic gound-holding policies for a network of airports. *Transportation Science*, 28:275–291, 1994.

[36] Vranas P.B.M, Bertsimas D., and Odoni A.R. The multi-airport ground holding problem in ait traffic control. *Operations Research*, 42:249–261, 1994.

[37] W. Philipp and F. Gainche. *Air Traffic Flow Management in Europe*, pages 64–106. Springer-Verlag, 1994.

[38] Hoffman R. and Ball M. A comparison of formulations for the single-airport ground-holding problem with banking constraints. *Operations Research*, 48(4):578–590, July 2000.

[39] Schouwenaars T., How J., and Feron E. Decentralized cooperative trajectory planning of multiple aircraft with hard safety guarantees. In *Proc. AIAA Guidance, Navigation and Control Conf.*, Providence, RI, August 2004. AIAA 2004-5141.

[40] Glover W. and Lygeros J. A multi-aircraft model for conflict detection and resolution algorithm evaluation. Technical Report WP1, Deliverable D1.3, HYBRIDGE, February 18, 2004.