HYBRIDGE

Distributed Control and Stochastic Analysis of Hybrid Systems
Supporting Safety Critical Real-Time Systems Design

WP1: Identification and modelling of uncertain hybrid systems

Safety relevant operational cases in Air Traffic Management

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November 14, 2002

Version: *1.2*
Task number: *1.1*
Deliverable number: *D1.1*
Contract: *IST-2001-32460 of European Comission*

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DOCUMENT CONTROL SHEET

Title of document:	*Safety relevant operational cases in Air Traffic Management*
Authors of document:	*O.J. Watkins and J. Lygeros*
Deliverable number:	*D1.1*
Contract:	*IST-2001-32460 of European Comission*
Project:	*Distributed Control and Stochastic Analysis of Hybrid Systems Supporting Safety Critical Real-Time Systems Design (HYBRIDGE)*

DOCUMENT CHANGE LOG

Version #	Issue Date	Sections affected	Relevant information
0.1	19/7/2002	All	First draft
0.2	6/9/2002	All	Revised based on reviewer's comments
1.0	18/10/2002	1, 5, A.2, A.3	Revised based on reviewer's comments
1.1	28/10/2002	2.3, 5.4, 5.5	Revised based on reviewer's comments
1.2	15/11/2002	A.2	Revised based on reviewer's comments

Version 1.0		Organisation	Signature/Date
Authors	O.J. Watkins	UCAM	
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	M. Moore	EEC	
	H.A.P. Blom	NLR	
	M.B. Klompstra	NLR	
	T. Lewis	BAES	
	M. Prandini	UniBs	

HYBRIDGE, IST-2001-32460
Work Package WP1, Deliverable D1.1

Safety Relevant Operational Cases in Air Traffic Management

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28/10/2002

Abstract

This is the first deliverable under work package WP1 of the HYBRIDGE project. The aim of the report is to provide a list of safety critical operational situations in air traffic management. A "gate to gate" view is presented of the safety critical situations an aircraft may encounter in normal flight conditions. Particular attention is devoted to cases likely to become more prominent as air traffic density increases. Motivated by the long term goals of WP1 (and the goals of WP3, WP5 and WP6 that make direct use of the results of WP1), the short-list is given with a particular emphasis on issues relating to conflict detection and resolution. In anticipation of the second deliverable of WP1, we also provide a brief discussion of the modelling issues that arise in the development of concrete mathematical models of the safety critical situations. The report concludes a short review of current conflict detection and resolution research. A brief outline of three classes of approaches to conflict detection is given: nominal, probabilistic and worst case.

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Contents

List of Acronyms

ADSB	Automatic Dependence Surveillance-Broadcast
ARTCC	Air Route Traffic Control Centre
ATC	Air Traffic Control/Controller
ATM	Air Traffic Management
BADA	Base of Aircraft Data
CDM	Collaborative Decision Making
CDR	Conflict Detection and Resolution
CTAS	Center-TRACON Automation System
FMS	Flight Management System
GPS	Global Positioning System
HMI	Human Machine Interface
MAAFAS	More Autonomous-Aircraft in the Future ATM System
MPC	Model Predictive Control
SUA	Special Use Airspace
TCAS	Traffic Alert Collision Avoidance System
TEM	Total Energy Model
TMA	Terminal Maneuvering Area (European equivalent of TRACON)
TRACON	Terminal Radar Approach Control (U.S. equivalent of TMA)
VOR	VHF Omni-directional radio Ranging

1 Objectives

Deliverable D1.1 is intended for participants of the HYBRIDGE project who are experts in control theory, path planning, etc. but not necessarily in Air Traffic Management (ATM). The main aim of the deliverable is summarised in Task 1.1 of WP1:

> "Make a short-list of operational cases where safety is a key issue when air traffic density increases, including a global identification of the main bottlenecks. Dense traffic operational cases will be identified for en-route, in the terminal manoeuvring area, around closely spaced runways and at airport surface. These operational cases will be used to keep the work in other work packages focused on distributed control issues that are of key importance for the application in mind."

The main contribution of D1.1 to the HYBRIDGE project is therefore the compilation of a list of safety critical ATM situations. This list is given in Section 3, using a "gate-to-gate" view (i.e. including ground operations, terminal operations, en-route operations, etc.). All the situations listed there should be familiar to ATM experts. These situations are meant to be used in the analysis and validation of Conflict Detection and Resolution (CDR) algorithms developed in WP3, WP5 and WP6 of HYBRIDGE. Many of the researchers involved in the development of these algorithms are not necessarily experts in ATM, but in other areas such as stochastic control, hybrid systems, path planning, etc. The discussion in Section 3 is meant to help them keep their work focused by identifying situations that their CDR algorithms and the analysis of their performance should concentrate on. To help the research in WP3, WP5 and WP6 get under way, in Section 5 we present a brief overview of recent developments in the area of CDR.

The second task of WP1 is to develop formal mathematical models for the safety critical situations identified in this deliverable. In Section 4 we identify features of the modelling language necessary to model the safety critical situations in Section 3.

References are listed in the end, in the order in which they appear in the text. We also provide an appendix with a list of key references used in compiling this report, as well as a short discussion of each one.

2 Air Traffic Management Status and Developments

2.1 Current Air Traffic Control Practice

Despite technological advances in avionics (including powerful on-board computers, advanced Flight Management System (FMS) positioning systems such as the Global Positioning System (GPS), and communication systems such as Automatic Dependence Surveillance-Broadcast (ADSB)) current ATM remains, to a large extent, rather simple, based around two elements:

1. A rigidly structured air space (Figure 1). Aircraft tend to fly along fixed corridors and at specific altitudes, depending on their route. The entire path of the aircraft is pre-planned (*flight plan*) and only minor changes are permitted on line.
2. A largely centralised, human operated control hierarchy. The ATC is in complete command of the air traffic and ultimately responsible for safety. All requests by the aircraft have to be cleared by the ATC.

Any changes in ATM practices to date tend to adhere to this structure and focus instead on modernising equipment, increasing computing power and improving the quality of the Human Machine Interface (HMI).

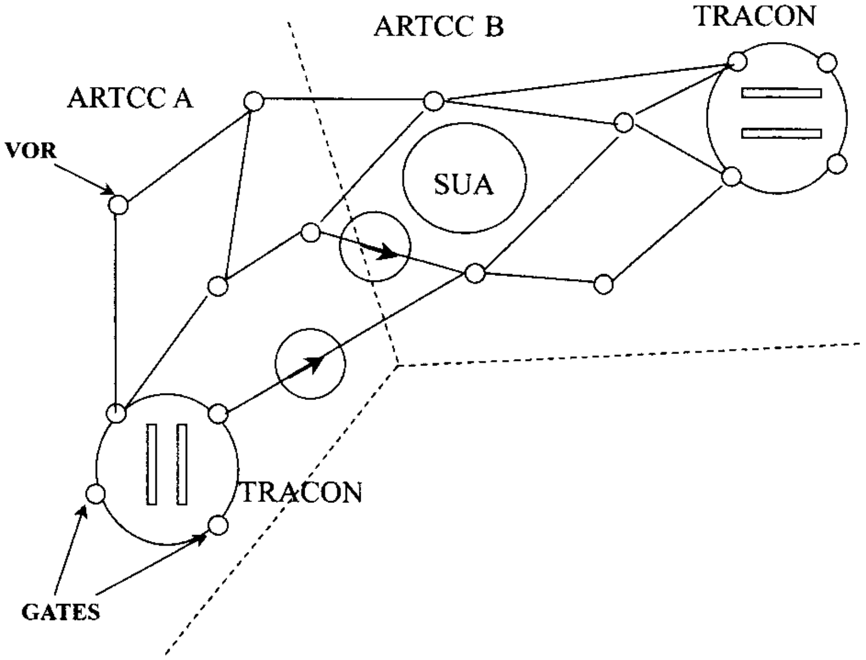

Figure 1: US ATM Structure, organised in Air Route Traffic Control Centres (ARTCC), Special Use Airspace (SUA) and Terminal Radar Control Areas (TRACON). The aircraft fly via way-points and enter the TRACON areas via gates. The European system is broadly similar, the essential elements being managed air space, no go zones, air corridors and arbitrarily defined ATM sectors.[1, Figure 1]

The ATM system developed in this way partly for historical reasons. Before the introduction of GPS aircraft needed to fly over specific VHF Omni-directional radio Ranging

(VOR) points on the ground, to get accurate information about their position. The current system structure, however, is also partly dictated by the limitations of the Air Traffic Control/Controller (ATC). The appeal of a system based on fixed routes and way-points is that the ATC needs to pay attention to only a few specific points in the airspace where conflicts are possible, e.g. way-points where routes intersect, entry points into the Terminal Manoeuvring Area (TMA), etc. The task would be much more difficult for the ATC if aircraft were allowed to fly arbitrary routes, since conflicts would be possible practically anywhere in the airspace.

The ATM system has operated reliably in this form for many years. The increasing demand for air travel is stressing it to its limits, however. Projections of air traffic levels range from an increase of 50% to 200% over the next 10 years [2]. This increase is likely to cause both safety and performance degradation in the near future, and place an additional burden on the already overloaded human operators. It is believed, for example, that it is one of the major causes that contributed to a 33% increase in controller error over the period 1996-2000 [3].

In summary, the main features of the current ATM system that are of interest to the CDR activities of HYBRIDGE are

Current system. ATC is in absolute control and is responsible for maintaining aircraft separation. There is very limited direct communication and virtually no coordination among the aircraft. Feedback and requests from the aircraft about the plans generated by ATC are also very limited (mainly routine changes in altitude to avoid turbulence, etc.). Information is exchanged by voice, secondary radar, etc. Autonomy is possible only in extreme situations, e.g. when Traffic Alert Collision Avoidance System (TCAS) issues an advisory [4]. The situation is depicted in Figure 2. In the figure, the solid lines represent the flow of commands, whereas the dotted lines represent the flow of information.

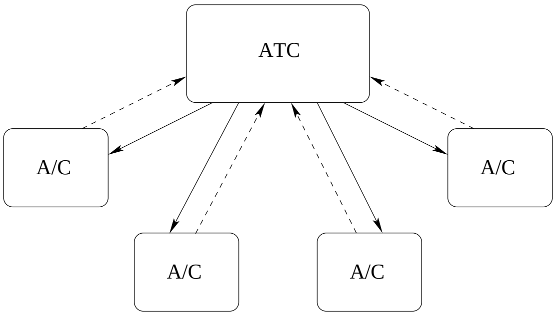

Figure 2: Current ATM system.

2.2 Potential Progression Toward Automation

It is possible that by increasing the level of automation, the efficiency of ATM can be improved and the tasks of human operators can be simplified. This may allow them to handle the increased demand in air traffic in a more reliable way, enhancing the level of safety over the current system. A number of different approaches to increasing the level of automation in the ATM process have been proposed in the literature (see, for example, [5, 6, 7, 8, 9, 10, 11]. Based on their implementation horizon they can roughly be classified as follows:

Near term. Data links and ADS-B are introduced, widespread use of GPS becomes standard, etc. ATC is still in absolute command and responsible for maintaining separation, but aircraft may be in direct communication with one another. Information is widely available. Limited changes to current practices and procedures to take advantage of technology/information. The work in [9, 10, 11] falls largely under this category, for example.

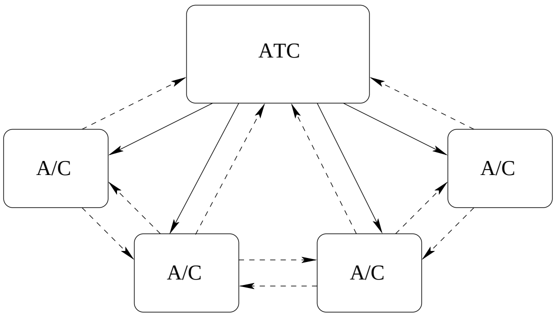

Figure 3: Near term changes.

Mid-term. Advanced ATC planning and assistance tools, conflict probes, etc. become standard. ATC is still in command and ultimately responsible for separation. However, the advanced tools allow more freedom in the use of the airspace. Planning is no longer tied down to the old route and way-point structure. ATC is free to guide aircraft anywhere in the airspace and relies on the tools to deal with the more complicated traffic patterns and conflict situations that may arise. As a consequence, ATC is also willing to accommodate flight plan changes generated by the aircraft based on local information, or the strategy of the airline; the tools are used to evaluate the global effect of these suggestions on the air traffic. For example, the work in [5, 6, 7] can be viewed as a first step in this direction.

Long term. The link among aircraft is strengthened and the decision making becomes more distributed. Tactical conflict detection and resolution functions are delegated

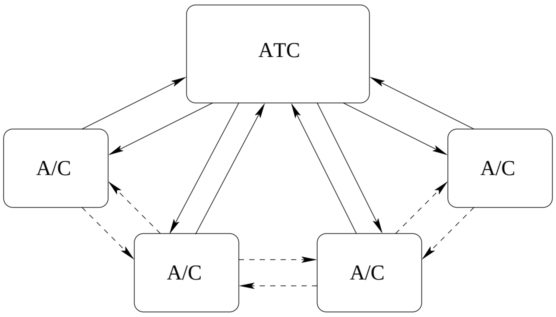

Figure 4: Mid-term changes.

to the aircraft. ATC retains a strategic role. For example, it is responsible for managing traffic densities, encounter configurations, etc. that the tactical planning methods used by the aircraft may have difficulty dealing with. The work in [8, 12] falls under this category.

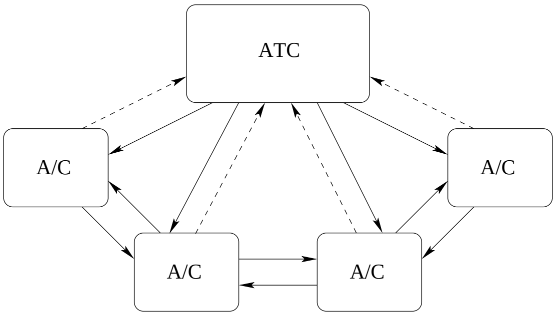

Figure 5: Long term changes.

Many envision the ultimate goal of this process to be *free flight* [8]. Even though there is no precise definition of the term, free flight roughly refers to an air traffic arrangement where the aircraft are free to plan their routes from origin to destination and resolve any conflicts with other aircraft in a distributed manner. It is envisioned that the process will be based on Collaborative Decision Making (CDM) tools [13] that allow a structured negotiation of routes, conflict resolution strategies, etc. among the "stake holders": the aircraft crews, the airlines and the ATC (which in this case plays the role of a passive observer, or arbiter).

2.3 Separation Assurance

Separation assurance forms a major part of the current ATC workload. If the level of automation in the ATM process increases, some of the separation assurance tasks can be transferred to the automated system. One approach for doing this is to rely on CDR strategies to assist ATC. CDR strategies predict the trajectory of aircraft within the managed airspace, analyse these trajectories to decide if there is a substantial possibility of loss of separation (conflict detection) and, if there is, issue advisories to the ATC and/or pilots on how to resolve the problem (conflict resolution).

To be able to validate the performance of automated and semi-automated CDR methods one has to demonstrate that they can cope with the most safety critical situations. The types of safety critical situations that need to be investigated can be very difficult to predict, especially with the more long term proposals mentioned above. Completely different airspace structures and ATM practices will be required by many of the systems in this category, compared to the current system. The types of problems that one may encounter may therefore be difficult to imagine before the details of the proposed system are fleshed out (possibly even after that, as our experience with similar problems in automated highway systems suggests [14].)

For the near-term and mid-term proposals, some intuition may be developed by studying safety critical operational cases in the current system. This report takes the first step in this direction and identifies a number of safety critical cases in current ATM practice, that can be used to guide the validation process of CDR algorithms developed in other HYBRIDGE work packages (e.g. WP3, WP5 and WP6). For this reason, a CDR point of view is adopted throughout the discussion.

In Section 3, a "gate to gate" view of the safety critical situations an aircraft may encounter in normal flight conditions is presented. Section 4 provides a preliminary discussion of the issues that arise when one tries to capture these situations in a concrete mathematical model. This discussion will serve as a link to Task 1.2 in WP1, the development of a mathematical framework for encoding the safety critical cases. The resulting models will serve as a basis for the development and validation of CDR methods. To highlight the issues that arise in this part of the process, a brief overview of current CDR approaches is given in Section 5. The discussion will also help to initiate the CDR work in WP3, WP5, and WP6 and put it in context. The appendix contains a list of the key references used in the production of this report and a brief discussion of the highlights of each one.

3 Safety Critical ATM Situations

This document is concerned primarily with safety critical situations that can be addressed using conflict detection and resolution strategies. Human related safety critical issues are the topic of WP7 of the HYBRIDGE project [15].

An issue not explicitly addressed in this report is the role of the airline in the safety process and its likely evolution if air traffic control restrictions are relaxed. At present airlines have minimal influence over flight plans once the aircraft is airborne. Therefore their role in safety critical cases in current ATM practice, the main topic of this report, is minimal. If aircraft get more freedom, however, there may be economic incentives for the airlines to interfere more. The effect this may have on CDR and therefore safety needs to be investigated. At the very least, developers of CDR algorithms need to ensure that their schemes appear fair: deviations may be equally distributed among aircraft in a particular conflict, or average out over multiple conflicts. In addition, it may be possible to introduce incentives for the airlines to collaborate instead of competing, at least for CDR purposes. The question is how the engineering and/or economics of the system may be structured to generate such incentives.

A number of safety critical situations may arise in ATM. An examination of causes of recent air accidents (Table 1) shows that many of these causes are hard to mitigate against (e.g. hijack and sabotage), while for others (such as ice/snow and wind shear) research in CDR provides no obvious benefit. Mid-air collisions and runway incursions, where effective CDR are particularly important, seem to be relatively rare events. It should be stressed, however, that currently a substantial amount of effort by ATC goes into preventing such situations from arising. The causes of mid-air collisions and runway incursions need to be identified, to ensure that the numbers are kept at the same level if automated systems that assist or partially replace the air traffic controllers are introduced.

3.1 Gate to Gate Safety Critical Situations

A complete flight is the movement of an aircraft from departure gate at one airport to arrival gate at the destination airport. Safety critical situations that may arise over the course of a complete flight are summarised below.

3.1.1 Taxiing

Runway based accidents are quite common, both when taking off and landing [16]. As the plane taxies to the runway the pilot must first obey all local circulation rules at the airport, take the correct route and avoid collision with other aircraft, ground vehicles (e.g. refuelling vehicles) and people. Getting lost and ground collisions are remarkably

US Carrier Accidents	%	Non US Carrier Accidents	%
Loss of Control	32	Loss of control	28
Other/unknown	18	CFIT	26
Controlled Flight Into Terrain (CFIT)	12	Other	10
Runway incursions	12	Landing	7
Ice/snow	9	Hijack	6
In-flight fire	6	Fuel exhaustion	5
Wind shear	3	Ice/snow	4
Landing	3	Sabotage	4
Sabotage	3	Runway Incursions	4
Hijack	3	In-flight fire	3
Mid-Air Collision	0	Wind shear	2
Fuel exhaustion	0	Mid-air Collision	1
Rejected Take-off	0	Rejected Take-off	1

Table 1: Causes of air traffic accidents 1987-1996 [3] (listed in the order of decreasing frequency).

common. The most dangerous form of incidents in this category are runway incursions, where an aircraft crossing a runway may find itself in the path of another aircraft that is landing or taking off. The most common cause of these incidents appears to be human error.

3.1.2 Take-off

During take-off manoeuvres are almost entirely prescribed, and do not generally pertain directly to the aircraft destination. Clearance for take-off will occur only when the target airspace is sufficiently clear. A plane taking off enters the TMA (referred to as “TRACON” in the United States).

3.1.3 Sector transitions in managed airspace

The transition from one airspace sector (e.g. a TMA) to another follows a highly prescriptive set of protocols. Aircraft are constrained to enter and leave airspace sectors through entry and exit points as shown in Figure 1. Passing through these points is managed by one set of air traffic controllers. The process involves responsibility for the aircraft being handed from one set of air traffic controllers to another. Loss of separation incidents are particularly common when changing airspace sectors [3]; from the point of view of the receiver air traffic controller the aircraft abruptly “appear” in their airspace.

3.1.4 Vertical crossing

It is likely that close to airports aircraft arriving from other destinations may intersect the path of the departing aircraft. The climb phase occurs over a large distance; the majority of the climb occurs after leaving the TMA, once the aircraft are within their air-corridors. These corridors are one-way, so loss of separation can be avoided. However, should steps be made toward more "free-flight" concepts, vertical crossing would require careful handling.

One issue that makes vertical crossings particularly challenging from a CDR perspective is that trajectory prediction in the vertical plane is notoriously difficult [17]. Part of the reason is that an aircrafts exclusion zone (area around the aircraft where it is considered unsafe for other aircraft to enter) tends to be smaller in the vertical direction than the horizontal. In addition, uncertainties in flight path prediction are also greater and harder to manage, due to factors about which the ATC has little information such as differences in aircraft weight, FMS settings, etc.

3.1.5 Trajectory constraints

For a variety of reasons, the flight paths of aircraft may be constrained to limited spaces during a flight. Stationary constraints, such as special use airspace (e.g. military airspace), may be planned for and as such are relatively easy to manage. Still, constraints due to special use airspace significantly reduce the carrying capacity of the airspace around them. This is a particular problem over Europe, where large sectors of airspace are "no-go".

Adverse weather also imposes constraints on the aircraft paths and is harder to manage as it is largely unpredictable, and may require en-route revision of flight plans. This type of constraint is responsible for many delays.

Problems associated with trajectory constraints may seem to be more procedural than safety related. However, the management of traffic as density increases around these areas is crucial. This is particularly true in the bad weather case, where because of the dynamic nature of the problem there may be no standard routing to ensure safe flight.

3.1.6 Spacing at cruising altitude in unmanaged airspace

Far away from tightly controlled air-spaces such as TMA's air traffic control may become more distributed, with aircraft assuming some of the responsibility for maintaining separation. This is especially true in oceanic airspace and remote locations (e.g. over parts of Africa) where radar and ATC coverage are sparse. In situations like these pilots may sometimes make use of the display and the traffic advisories of TCAS as an additional source of information.

To account for the potentially limited information available in these areas, the exclusion zones around aircraft may be increased significantly. Such separations are generally straightforward to maintain due to the low air traffic densities in these areas. In some situations, however, lateral passing manoeuvres may be required, when a fast aircraft finds itself behind a slower one in the same corridor. The nature of these manoeuvres tends to reduce separation, and thus requires careful handling.

Vertical crossing manoeuvres also become more complicated in this case. One aircraft may have to cross the flight level of another aircraft with limited information about the intents of the other aircraft and without explicit clearance from ATC.

3.1.7 Arrival in managed airspace

After leaving the unmanaged airspace, the aircraft must re-enter managed airspace. As for the transitions between sectors in managed airspace (Section 3.1.3) this must be accomplished via specific points in the airspace, in consultation with air traffic controllers. Due to position uncertainties, it is not easy to manage when this transition occurs exactly (this is especially true for older aircraft not equipped with GPS). This uncertainty makes it hard to manage the workload of air traffic controllers, who may not be able to manage the transfer of responsibility in conjunction with their other tasks.

3.1.8 Terminal approach

Exactly like departure from an airport the sequence of manoeuvres required when arriving at an airport is highly prescriptive. Air traffic density reaches a peak and the standard approach procedure ensure that traffic regulation remains as simple as possible. This does result in substantially sub-optimal flight paths, the approach manoeuvre being independent from the direction of arrival.

A particularly dangerous situation that arises in this phase of the flight is a missed approach. In some cases the aircraft or ATC may decide that it is impossible to land with the current approach. The reasons may be traffic on the target runway (see also Section 3.1.9), or deviation from the approach pattern due to extreme weather conditions that make landing impossible or dangerous. In this case the approach is aborted and the aircraft has to rejoin the traffic waiting to land. This phase is particularly dangerous since the aircraft may have to be merged with traffic taking off from the same airport at very short notice.

3.1.9 Landing

Landing shares some of the problems of take-off. The main requirement is that the runway is clear. Assuming the aircraft is attempting to land at the correct runway (not always the case [16]) this entails sufficient clearance between successive landings, and keeping the runway clear of airport traffic.

After landing the pilot may be faced with an unfamiliar airport, and must then surmount the problems described in Section 3.1.1.

3.2 Short-list of CDR Specific Cases

If separation can be maintained during each of the above phases of flight then conflict free routing will be assured. Automated or semi-automated CDR can play a role in improving safety during all flight phases. Its impact, however, is likely to be greater in some phases (e.g. for vertical crossings and aborted approaches) than in others (e.g. taxiing and runway incursions).

Based on the above discussion, the safety critical operational situations where advanced CDR methods are likely to be most fruitful appear to be:

1. Vertical crossings in all airspace, and especially in unmanaged airspace.
2. Overtake manoeuvres in unmanaged airspace.
3. ATC sector transitions, especially at the entry/exit points of TMA.
4. Missed approaches.

Of these, 1, 2 and 3 occur regularly in nominal operations, whereas 4 typically involves substantial deviation from the nominal conditions. CDR schemes under the short term and mid term classes discussed in the introduction should be able to address situations in 1, 3 and 4. CDR methods developed for the long term automation proposals discussed in the introduction may be better suited for situations 1 and 2 in unmanaged airspace, due to the inherently distributed nature of the problem.

4 Model Based CDR

4.1 Modelling Needs for CDR

Models of the safety critical situations are needed in different phases of the CDR process.

Conflict Prediction. Models are needed to predict the "future" of an encounter to determine whether it is likely to lead to a conflict or not.

Conflict Resolution. Models are also useful for conflict resolution. In the simplest case, possible resolution manoeuvres can be analysed in an "if-then" manner, with the model being used to predict the implications of each one. Moreover, most of the conflict resolution strategies based on control theoretic and path planning methods rely on an underlying model to generate the manoeuvres and analyse their performance. Model Predictive Control (MPC) methods provide a way of combining "if-then" model based predictions with a structured search procedure based on optimisation.

Validation. Validation is a crucial step in the development of CDR algorithms. Much of the work in CDR involves constructing theoretical arguments about the performance of the algorithms. However, all CDR methods have parameters that need to be chosen to optimise their performance in practice. Moreover, one needs to make an argument that CDR methods will work based on something more than theoretical calculations.

Eventually the algorithms will have to be validated in *field trials* involving air traffic controllers. This type of validation is likely to be very costly and time consuming and is beyond the scope of the HYBRIDGE project.

An alternative may be to try to validate the algorithms on *real data*. This approach is appealing, but has a number of drawbacks:

- Flight track data is difficult to find (usually proprietary). Conflict data is of course particularly sensitive.
- Conflict situations are (thankfully) extremely rare. Track data includes implicitly the actions of the air traffic controllers, whose job is precisely to prevent conflicts from occurring. To validate our algorithms, on the other hand, we would like to identify situations that would result in a conflict *if ATC were to take no action*. We would then notify ATC if one of these situations arises to ensure that *they do take action*.

Despite of these, real data has been used in the literature to validate algorithms. For example, in [18] the second problem listed above was circumvented by discarding flight path pairs at the same altitude, and testing the conflict detection algorithms as if pairs of aircraft at different altitudes were at the same level. A similar effect can be achieved by shifting and rotating real aircraft tracks to make them appear like conflicts [19]. It should be noted, however, that this approach is likely to affect the statistical properties of the tracks. For example, all information on the correlation of aircraft positions (due to correlation in the wind at different places in the airspace) is likely to be lost. Moreover, collection of data remains problematic.

Another alternative is to validate the algorithms on *synthetic data*. The idea here is to simulate a realistic model of the aircraft and weather conditions and use the data generated by the model as the “real world”. This approach does not suffer from any of the disadvantages listed above. The problem is that it requires one to develop and tune a realistic model of how aircraft fly (from the point of view of ATC) as well as the uncertainty that enters into the process (due to a large extend to wind, but possibly also to under-modelling and other factors).

4.2 Required Features of the Modelling Framework

To cover the modelling needs of CDR methods, a modelling language that is rich enough to capture all of the safety critical situations listed above is needed. A high level analysis of the safety critical situations suggests that the modelling framework needs to have a number of properties.

4.2.1 Continuous Dynamics

Vertical Crossing. Continuous dynamics are dominant in vertical crossing situations. In this case the continuous dynamics are mostly restricted to the vertical plane. They can be adequately modelled by a point mass model and energy balance equations [20, 21]. A more detailed discussion of this type of model is given in Section 4.3.

Overtake. Continuous dynamics are also important for overtake manoeuvres. Overtake manoeuvres in unmanaged airspace take place primarily at cruising altitudes. Altitude changes during the manoeuvre are likely to be small and therefore the continuous dynamics will be predominantly in the horizontal plane. In Section 4.3 a short discussion of the modifications needed for point mass models to capture such horizontal motion is given.

Sector Transitions. Accurate models of continuous dynamics seem to be less important for sector transitions. In certain cases it may also be possible to separate the vertical and horizontal components of the continuous model. Specifically for transitions at the TMA gates the horizontal and vertical may interact, since aircraft may be climbing when leaving the TMA or descending when entering it.

Missed Approaches. Missed approaches involve the closest coupling of the horizontal and vertical components. Whether an approach is aborted or not may depend on the combination of horizontal and vertical positions, in addition to external factors such as a runway incursion, or wind shear.

4.2.2 Discrete Dynamics

Vertical Crossing. The discrete dynamics in vertical crossing situations are rather limited. The only obvious discrete component involves the flight levels. For example, the motion of an aircraft will change dramatically when it levels off at the desired flight level. Crossing of flight levels where other aircraft may be moving is another discrete phenomenon that may be important for CDR purposes.

Overtake. The discrete dynamics in overtake situations are also limited. Initiation and termination of the manoeuvre are the two more prominent discrete phenomena. Depending on how the manoeuvre is executed, a distinction may also have to be drawn between the different phases of the manoeuvre.

Sector Transitions. Sector transitions are intrinsically discrete phenomena. The state of the system undergoes a transition when an aircraft changes sector and is handed of from one ATC to another. One needs to ensure that the aircraft will find itself in a safe configuration in the new sector before the transition is allowed to go ahead. If not (for example, if the traffic density in the new sector is already too high) the transition should be delayed. In this case, one has to ensure that it is safe for the aircraft to remain in its current sector.

Currently all these tasks are performed by ATC based on established procedures. Some flexibility is allowed depending on traffic conditions; for example an air traffic controller may delay accepting a flight coming into a sector if there are more urgent problems to deal with. Introducing automation safely requires full understanding of these procedures. One would have to ensure, for example, that the system does not give rise to situations where an aircraft can neither be handed on nor remain in the current sector safely.

Missed Approaches. Missed approaches also contain an intrinsically discrete component: whether the approach is aborted or not. The “go around” manoeuvre may require additional discrete choices, such as vectoring commands and additional way points.

4.2.3 Uncertainty

Vertical Crossing. The primary source of uncertainty in this situation is the continuous motion. Climbing rates depend on the aircraft weight, which may vary widely with aircraft type, route (and hence fuel), number of passengers, type of cargo, etc. Additional uncertainty comes from the settings of the FMS. All this information is (at best) only partially known to ATC.

Uncertainty in the continuous motion also induces uncertainty in the discrete transitions. The time at which the aircraft will reach a particular flight level and its horizontal position at that time may be difficult to predict with accuracy. This is important if conflicts are to be avoided with other aircraft moving at that flight level.

Overtake. The main source of uncertainty here seems to be the weather and in particular wind. This again affects primarily the continuous motion of the aircraft.

Sector Transitions. There is some uncertainty in the time at which a hand-off from one sector to the other will take place. The exact timing of the transition may depend on the traffic in both sectors. Hand-off may take place earlier if traffic in the current sector is heavy, or may be delayed if traffic in the receiving sector is heavy. The effect of this uncertainty tends to be small in current conditions, but may become more pronounced as traffic densities increase.

Missed Approaches. The cause of the missed approach may be modelled as probabilistic. It may involve either the continuous motion or a discrete occurrence (e.g. a runway incursion). There is also uncertainty in whether the aircraft goes ahead with the current approach or whether it goes around. In the latter case, the timing of the decision is another source of uncertainty.

4.2.4 Composition

A model of the entire ATM scenario associated with the above safety critical situations needs to include different interacting components. Components will be needed for each of the aircraft involved, the ATC and the weather conditions. For some tasks (e.g. validation) the CDR algorithms may also have to be treated as a component in the model. Depending on the level of detail required, each of these components may have to be refined further; for example, the model for an aircraft may be decomposed into separate models for the dynamics, the flight plan, the FMS, etc. [22].

A compositional language that allows one to model each of these components separately and then put them together using appropriate composition operators is clearly desirable. Composition may be easy to perform for some components (e.g. the aircraft and FMS models). However, composition methods for general stochastic hybrid systems models are not currently available in the literature. Work packages WP2 and WP4 of HYBRIDGE aim to fulfil these needs, at least for certain classes of stochastic hybrid systems.

4.3 The BADA Model and Possible Improvements

Eurocontrol maintain the Base of Aircraft Data (BADA) which contains operating characteristics for over 100 aircraft, including virtually all of those operating over Europe. A manual for the database is also provided [20]. It includes amongst other things:

- A proposed flight model, aimed specifically at simulating flight in the vertical plane;
- Equations for air density and temperature as functions of altitude;
- Operating schedules specifying air speeds in specific altitude intervals etc.
- Simple relations for drag coefficients and fuel consumption rates.

The flight model is a Total Energy Model (TEM) relating the energy available through excess thrust (Thrust - Drag), to changes in height and lateral velocity. The most complex elements of the model relate to how this energy is shared between climbing and accelerating. The data files available through BADA also contain specifications of lift and drag coefficients, nominal masses, cruising velocities etc. for a large number of aircraft makes.

One shortcoming of BADA is the lack of data on the effects of cross-winds - the “side force” coefficients, that determine to what extent a plane may be blown off course [23]. If these can be determined, it will enable a complete 6 degree of freedom model to be developed, which coupled with the BADA data, will enable accurate flight simulations. At present only 5 degrees of freedom may be modelled.

5 Current Work on CDR

We conclude D1.1 with a brief overview of some CDR techniques, included principally for the benefit of readers less acquainted with the detail of air traffic management. We cite a review paper, which introduces a classification of methods of conflict detection and resolution, then move onto an overview of three techniques for aircraft trajectory prediction for the purpose of conflict detection.

A good source for information on CDR techniques is reference [24]. The authors of [24] surveyed 68 recent papers, detailing existing and proposed CDR techniques. The general form for each of them is:

1. Predict the 4D trajectories of each aircraft over a short or medium term time horizon (e.g. up to 20 minutes).
2. Apply conflict detection algorithms, estimating the level of criticality of the current airspace configuration.
3. If the conflict detection algorithms return a sufficiently high level of criticality issue a conflict advisory alert. For algorithms with conflict resolution facilities, a resolution advisory may also be issued at this stage.
4. Repeat the above steps periodically e.g. at each radar sampling interval (roughly 12 seconds).

There are of course exceptions to this general outline. For instance, [25, 12] propose a more abstract solution, using the hybrid systems "reachability concept" to test if an exclusion zone is within the reachable set of another aircraft; if not, then separation is assured.

Even though there is a substantial amount of research into automated and semi-automated CDR, such methods have yet to be extensively deployed in the ATM system. One system that has become a standard is the Traffic Alert and Collision Avoidance System (TCAS) [4]. This is an on-board system that issues emergency advisories when the situation becomes so critical that a mid-air collision is imminent. TCAS is a "last chance" system; in managed airspace it should in principle never have to issue advisories since ATC is expected to detect and resolve potentially dangerous situations before a collision becomes imminent. At the ATC level, the CTAS system (Center-TRACON Automation System [5, 26, 27]) is currently being field tested by NASA in the United States. The algorithms implemented in CTAS issue conflict advisories, the air traffic controllers are then responsible for resolution.

5.1 Classification of methods

Kuchar and Yang [24] classify each CDR method according to a variety of criteria:

1. **Dimensions of state information.** Even though ideally CDR methods should be able to deal with 3D motion of aircraft, some methods have been either demonstrated in the horizontal case (e.g.[1, 28]), or concentrate specifically on the problems associated with trajectory uncertainties in the vertical plane (e.g. [29]).

2. **Method of trajectory estimation.** The most common trajectory estimation is based on a nominal model. With the nominal approach the algorithm predicts the future positions of aircraft based either on a simple extrapolation from a known position and velocity, or a combination of such an extrapolation and intent information (e.g. the flight plan). An alternative is to use a worst case approach. In this case, hard bounds are assumed on the possible deviations from a nominal trajectory. The algorithms then try to determine the worst possible situation from within these bounds. Finally, some models use a probabilistic description of position. All the current models of this type (see for example [30, 31, 32, 27, 33, 1, 34]) describe the position of the aircraft in the future as a probability distribution. The distribution is typically Gaussian, though some methods allow more general types of distributions [31, 34, 33]. The mean of the distribution is the nominal position of the aircraft. The covariance matrix typically grows the further we try to project the positions into the future, to reflect the increasing uncertainty of our predictions. With probabilistic models, conflict prediction typically involves the computation of a probability of conflict, probability of collision, etc. based on these models.

3. **Is there explicit generation of conflict alert?** Some methods conclude with generating conflict probabilities, and do not issue an explicit alert. Most of the papers concerned with conflict resolution include explicit alerts.

4. **Conflict Resolution method.** Many methods of resolution have been proposed, the simplest of which prescribe manoeuvres or trajectory changes upon receipt of a conflict alert. These standard manoeuvres should result in resolution, if not then another conflict alert is issued, and the process is repeated. Some authors have attempted to optimise their resolution procedures using a set of cost metric which evaluate safety, simplicity and cost-efficiency [35]. The set of manoeuvres allowed and the formulation of the cost functions determine the results. One approach is to use “potential field methods”. Roughly speaking, the idea is to model the aircraft as charged particles. Depending on the “charge” applied to each aircraft the repulsive force between them should be sufficient to maintain separation. Much of the work with this approach is on resolving the minority of conflict situations in which the charged particle approach results in impossible manoeuvres [36]. Finally, and most

basically, is the manual resolution approach in which the operator is required to resolve the conflict based on their expertise and experience, possibly using additional information provided by the automation system e.g. [6].

5. **Manoeuvring dimension of resolution procedure.** Most methods of resolution constrain their aircraft to use a limited set of manoeuvres when resolving conflict. Most combinations of speed change, lateral movement and vertical movement are used.

6. **Management of multiple aircraft conflicts.** In general each pair of aircraft is considered individually, until all pairs have been considered. In the case of conflict resolution the procedures are iterated until a conflict free situation is achieved. Some methods attempt a global solution, which in a very densely packed airspace may be more efficient that the pairwise approach.

We conclude the report by a brief overview of the three different approaches to predicting aircraft position: *nominal*, *probabilistic* and *worst case*. In their current state weaknesses in each approach may easily be seen. A truly nominal approach, for instance, does not include any error modelling, and is thus inherently inaccurate (the work cited in section 5.2 does, however, go on to consider position errors). The probabilistic approach described takes an oversimplified view of the probability distribution, thus compromising its effectiveness. The worst case approach is clearly over conservative. Despite their shortcomings these approaches give a basis upon which a new CDR technique may be built.

5.2 Nominal Approach

The methods used by different authors in this area vary, but share the same basis. Several different approaches may be found in [28, 17, 37, 6], here we firstly give a very simple illustration of the 2D problem (based on [28]) then review the 3D case, as approached in [17].

5.2.1 Encounter Geometry in 2 dimensions

In this approach the exclusion zone around an aircraft is given by a circle, of radius s (typically 5nmi):

$$\mathcal{C} = \{(x_r, y_r) | x_r^2 + y_r^2 < s^2\}, \tag{1}$$

in which x_r and y_r are the coordinates of the of the *intruder* aircraft relative to the *host* aircraft (or *ownship*). The nominal trajectory approach admits a closed form solution,

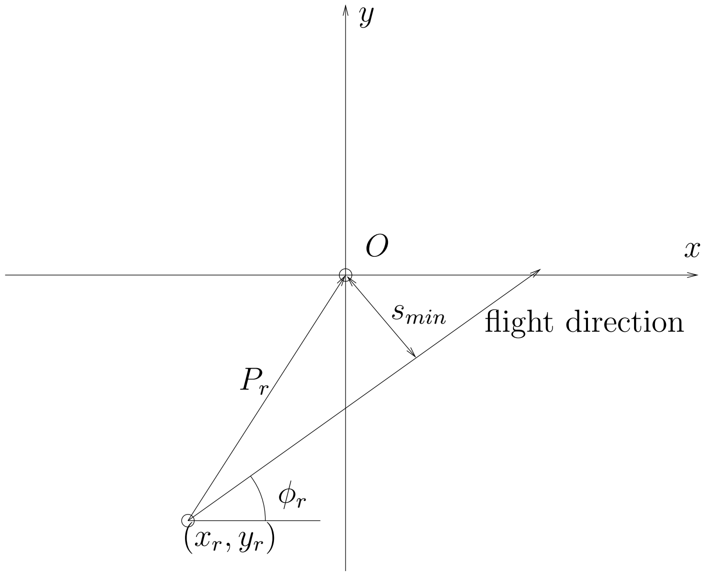

Figure 6: 2D encounter geometry. O is the origin, P_r the initial vector between the two aircraft and s_{min} the minimum separation between the two.

uniquely among conflict detection methods. A very straightforward vector geometry approach may be taken.

If the host aircraft is fixed at the origin, then the position of the intruder is described by the locus of the point (x_r, y_r). Assuming that the relative speeds of the aircraft remain constant this locus will be a straight line, in the direction of the relative heading angle, ϕ_r. Figure 6 shows the geometry of the situation.

The minimum separation, s_{min}, may be found using vector geometry. Let $P_r := [x_r, y_r]^T$ denote the position of the intruder relative to the host. Then define $\hat{n} := [\cos\phi_r, \sin\phi_r]^T$ to be the unit vector in the relative flight path direction ϕ_r. The minimum separation is then given by

$$s_{min} = |P_r \times \hat{n}|. \tag{2}$$

If this value is less than the acceptable minimum separation, s, then there will be a conflict and a suitable alert should be issued.

5.2.2 Generalisation to three dimensions

Numerous papers have concentrated on 3D conflict detection e.g.[38, 17, 12], here we summarise [17]. The 3D generalisation is not entirely straightforward. The exclusion zone in 3D is a cylinder extending a distance H (depending on altitude, typically 1000ft) above and below the aircraft.

The 3D case situation is more challenging, due to the difference in geometry between the horizontal and vertical dimensions of the exclusion zone. We now fix the intruder aircraft at the origin, and consider the relative flight path of the ownship past the exclusion zone. In 3D the exclusion zone is described by:

$$\mathcal{C} = \{(x_r, y_r, z_r) \mid x_r^2 + y_r^2 < s^2, \ -H \leq z_r \leq H\} \tag{3}$$

where z_r is the difference in altitude between the ownship and the intruder and, as before, x_r and y_r are the horizontal coordinates of the of the intruder relative to the host. The approach in this paper is to find a $t > 0$ where the ownship enters the protected zone, assuming that there is no conflict at $t = 0$. This t exists if the trajectory intersects twice the surface of the cylinder P. The cylinder surface consists of its lateral surface:

$$\mathcal{C}_1 = \{(x_r, y_r, z_r) \mid x_r^2 + y_r^2 = s^2, \ -H < z_r < H\} \tag{4}$$

And the top and bottom bases:

$$\mathcal{C}_2 = \{(x_r, y_r, z_r) \mid x_r^2 + y_r^2 < s^2, \ |z_r| = H\} \tag{5}$$

Assuming that $\dot{z}_r \neq 0$ (which would give the 2D case) a set of possible conflict situations are presented.

1. $-H < a_z$ and $-a_x > D$, where a_x and a_z the horizontal and perpendicular distances between aircraft, as shown in Figure 7. In this case the boundary of the cylinder surface that may be intersected is given by:

$$B_1 = \{(x_r, y_r, z_r) \mid x_r = D^2/a_x, \ \text{or} \ |z_r| = H, \ x_r < D^2/a_x\}, \tag{6}$$

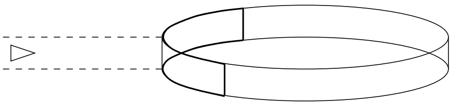

Figure 7: Geometry of case 1

2. $a_z \leq -H$ and $-a_x \geq D$ as shown in Figure 8. The boundary of the cylinder surface that may be intersected is given by:

$$B_2 = \{(x_r, y_r, z_r) \mid x_r = D^2/a_x, \ \text{or} \ z_r = H, \ x_r < D^2/a_x, \ \text{or} \ z_r = -H, \ x_r > D^2/a_x\} \tag{7}$$

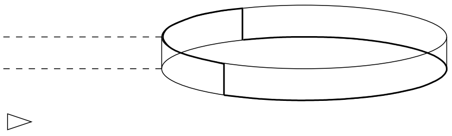

Figure 8: Geometry of case 2

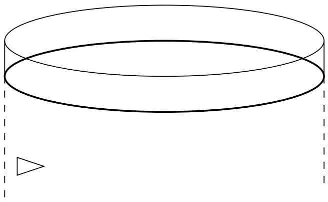

Figure 9: Geometry of case 3

3. $a_z < -H$ and $-a_x CD$ as shown in Figure 9. The boundary of the cylinder surface that may be intersected is given by:

$$B_3 = \{(x_r, y_r, z_r) \mid z_r = -H\} \tag{8}$$

For each of these cases a simple geometric conflict test may be developed. In [17] this is performed simultaneously with the development of conflict resolution algorithms. This discussion, however, is more concerned with conflict detection, so we shall now consider the extension of the nominal approach above to a probabilistic case.

5.3 Probabilistic Approach

One approach for capturing uncertainty is to model the flight of the aircraft using a stochastic differential equation or, more generally, a stochastic differential equation with switches. This is, for example, the approach used in the computation of the in-crossing rate [31, 34].

The most common approach to this problem is to simply add a normal distribution to the nominal position of the aircraft. This is the approach taken in [26, 27, 1] for example (also parts of [32, 33]). The discussion here is based on [1], which is restricted to the level flight (2D) case, but gives an illustration of the approach involved. The work of [28] also goes on to consider along-track errors in plane position, then cross-track errors.

5.3.1 Prediction Model

In [1] a flight plan is modelled as a series of way-points $\{P_j\}_{j=0,...,n}$, $P_j \in \mathbb{R}^2$ and a sequence of speeds, $\{v_j\}_{j=0,...,n}$, $v_j \in \mathbb{R}_+$ for moving between way-points. All way-points which have been passed are discarded and the first way-point P_0 describes the current position of the plane. The main source of uncertainties is considered to be the perturbation to the aircraft motion over time, which quickly overwhelms any initial error in P_0. Prediction of nominal position at any time is simple to calculate. First the nominal arrival times at each way-point are calculated recursively:

$$T_j = \frac{\|P_j - P_{j-1}\|}{v_j} + T_{j-1} \tag{9}$$

starting with T_0, the current time. The nominal distance travelled $s(t) \in \mathbb{R}_+$ may then be calculated:

$$s(t) = v_j(t - T_{j-1}) + s(T_{j-1}) \tag{10}$$

again, calculated recursively. Similarly the nominal position $p(t) \in \mathbb{R}^2$ is given by:

$$p(t) = p(T_{j-1}) + \frac{v_j(t - T_j - 1)(P_j - p(T_{j-1}))}{\|P_j - p(T_{j-1})\|} \tag{11}$$

with $j = 1, ..., n$, initialised with $s(T_0) = 0$ and $p(T_0) = P_0$.

This predicted position may then be compared with the actual position to give the along track and cross track errors. These errors are influenced by uncertainty, both in terms of flight dynamics and external factors such as wind. The work of [26, 27] suggests that these errors may be modelled as a multivariate Gaussian random variable. Let $x(t) := (x_1(t), x_2(t)) \in \mathbb{R}^2$ be the aircraft predicted position at time t. Assume that $x(t)$ is normally distributed $x(t) \sim \mathcal{N}(m(t), V(t))$ with mean $m(t) = p(t)$. The covariance matrix $V(t)$ is assumed to increase with time in every direction, reflecting an increase in uncertainty as the prediction horizon increases.

It is assumed that the variances in the along-track and cross-track positions grow according to the following two equations:

$$\sigma_a^2(t) \sim r_a^2 t^2, \tag{12}$$

$$\sigma_c^2(t) \sim min\{r_c^2 s^2(t), \bar{\sigma}_c^2\} \tag{13}$$

So $\sigma_a^2(t)$ grows quadratically with time elapsed, and $\sigma_c^2(t)$ grows quadratically with the distance travelled, until it saturates at a fixed value $\bar{\sigma}_c^2$. This model (first proposed in [26, 27]) reflects the efforts of the pilot to correct cross track errors in the short term, and along track errors in the long term (longer, at least, than the 20 minute horizon of this model).

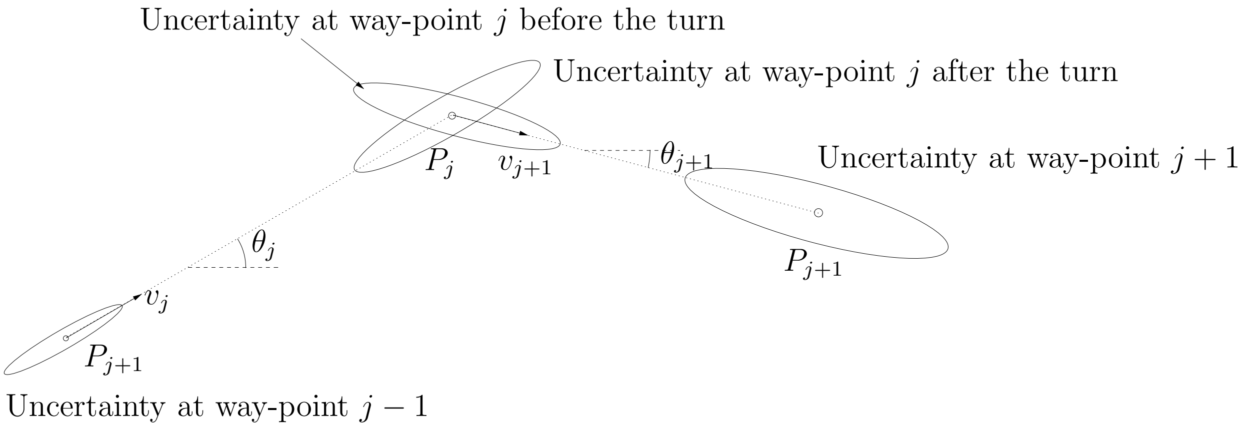

Figure 10: Section of aircraft flight plan, showing growth of uncertainty with time

Figure 10 shows the prediction model for the aircraft motion. The ellipses represent equiprobability curves of the distribution $N(m(t), V(t))$. Note the discontinuity of the predicted error at the way-points. A more realistic nominal trajectory model would eliminate this discontinuity.

5.3.2 Conflict Detection Algorithm

Based on the definition of a flight plan in Section 5.3.1 we may describe an N aircraft encounter by the configuration, γ, which consists of the flight plans of all aircraft:

$$\gamma = \{\{P_j^i\}_{j=0,\dots,n_i}, \{v_j^i\}_{j=1,\dots,n_i}\}_{i=1,\dots,N} \tag{14}$$

In the probabilistic case conflict cannot be determined as a digital yes/no state, so a measure of criticality $C(\gamma)$ is extracted from the configuration. This is compared to a threshold value $\bar{C}$ and a conflict is declared if the threshold is exceeded. This process is repeated at each change of γ (e.g. at each radar scan).

In a probabilistic setting, the criticality of an encounter is typically quantified by the probability of one aircraft entering the exclusion zone around another aircraft. Different ways have been proposed for computing and using this probability. In [27] an analytical approximation of an average value of the probability of conflict is derived. The formula can be used in very fast calculations, but its exact interpretation is unclear. In [33] Monte-Carlo simulation is proposed as a method for computing the probability of conflict. The flexibility of the simulation allows one to incorporate a number of interesting additions and variations to the prediction model. However, this method may be unsuitable for on-line implementation, because Monte-Carlo simulation tends to be computationally demanding.

In [1] the following measure of criticality is proposed. Consider two aircraft A and B, flying at the same altitude and let x^A and x^B denote their positions. Denote the probability density function for the separation $d(t) := x^A(t) - x^b(t)$ by $P_{d_t}(y)$. The instantaneous probability of conflict $P_C(t)$ is then given by:

$$P_C(t) = \int_{y \in \mathcal{C}} P_{d_t}(y) dy, \tag{15}$$

where $\mathcal{C}$ denotes the area of conflict. The criticality measure over a finite horizon T is defined as

$$C(\gamma) := \max_{t \in [0,T]} P_C(t) \tag{16}$$

Based on the model described in 5.3.1 the separation $d(t)$ may be calculated. The position of each aircraft is given by $x^i(t) \sim \mathcal{N}(m^i(t), V^i(t)),\ i = A, B$. The separation is thus given $d(t) \sim (\mu(t), Q(t))$, with mean $\mu(t) := m^A(t) - m^B(t)$ and covariance matrix $Q(t) := V^A(t) + V^B(t)$. Note that this assumes that x^A and x^B are uncorrelated, which will not generally be the case. If two aircraft are close enough to be in conflict it is likely that the wind acting on each of them will be quite closely correlated, thus the covariance will not be a simple summation of $V^A(t)$ and $V^B(t)$. Including the effects of such a correlation will be a focus for further work.

In [1] a randomised conflict detection algorithm is proposed based on $C(\gamma)$. The algorithm calculates an approximation of $P_C(t)$ using randomised extractions. The method ensures a certain level of accuracy for the obtained approximate value of $C(\gamma)$.

5.4 Worst Case Approach

The discussion of the worst case approach is based on [12]. Rather than taking an initial condition and projecting forward, the approach is to determine which set of initial conditions ensure safe flight given an optimal control strategy for the ownship, and an uncooperative intruder which seeks to minimise separation. This essentially describes an approach for avoiding another aircraft in a 'dog-fight'. The aim of this approach is not to resolve conflict, but to identify flight plans in which conflict is impossible. Here the 2D case is described, [12] extends the argument to 3D.

For completeness we include the essential mathematical steps in this approach, which are necessarily quite complex. Some advanced concepts are utilised, including the notion of predecessors, differential game theory and optimal control. Readers may prefer to concentrate on the description of the approach, rather than the detail.

Firstly the relative motion of the two aircraft is determined, based on the differential equations governing their positions:

$$\left.\begin{array}{l} \dot{g}_1 = g_1 X_1 \\ \dot{g}_2 = g_2 X_2 \end{array}\right\} \Rightarrow \dot{g}_r = g_r X_2 - X_1 g_r \tag{17}$$

Where g_1 and g_2 give the positions and directions of aircraft 1 and aircraft 2 respectively. Mathematically, g_1 and g_2 are elements of the Lie group of positions and orientations in the plane and X_1 and X_2 are elements of the associated Lie algebra (roughly, the space of linear and angular velocities. g_r is the relative configuration of the two aircraft, in terms of the relative positions x_r, y_r and the angle between them ϕ_r. In the standard representation one can write

$$g_r = \begin{bmatrix} \cos\phi_r & -\sin\phi_r & x_r \\ \sin\phi_r & \cos\phi_r & y_r \\ 0 & 0 & 0 \end{bmatrix} \tag{18}$$

which, as one would intuitively expect, represents a rotation and translation. X_1 and X_2 are then represented as matrices in $\mathbb{R}^{3\times3}$:

$$X_1 = \begin{bmatrix} 0 & -\omega_1 & v_1 \\ \omega_1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \; X_2 = \begin{bmatrix} 0 & -\omega_2 & v_2 \\ \omega_2 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{19}$$

We may thus infer the relative configuration dynamics:

$$\dot{x}_r = -v_1 + v_2\cos\phi_r + \omega_1 y_r \tag{20}$$

$$\dot{y}_r = v_2\sin\phi_r - \omega_1 x_r \tag{21}$$

$$\dot{\phi}_r = \omega_2 - \omega_1 \tag{22}$$

Equation (20)–(22) describe a kinematic model for the relative movement of the two aircraft, governed by a differential equation in the standard form

$$\dot{x} = f(x, u, d) \tag{23}$$

The state is $x = (x_r, y_r, \phi_r) \in \Re^3$, the relative configuration of the two aircraft. The evolution of the state is influenced by a control input $u = (v_1, \omega_1) \in \Re^2$ (the linear and angular velocities of the ownship and a disturbance input $d = (v_2, omega_2) \in \Re^2$ (the linear and angular velocities of the intruder).

The problem of separation assurance is then cast as a non-cooperative game between the actions of the ownship, u, and the actions of the intruder, d. u “wins the game” from a particular state if it can choose its actions such that for all possible actions of d and for all future times the state of the aircraft does not enter the unsafe set of states $\mathcal{C}$ (defined as in Section 5.2.1). The goal is then to find the set of states from which u wins the game; if the system starts in one of these states we know that a conflict can be avoided by an appropriate action of the ownship, irrespective of the actions of the intruder. Notice that resolution with this approach is naturally distributed, each aircraft makes its decisions separately, assuming the worst for all other aircraft.

The calculation of the winning states of u is done using tools from game theory and optimal control. Consider a function $l(x)$ such that $\mathcal{C} = \{x \in \mathbb{R}^n | l(x) \leq 0\}$ (in this case, one can take $l(x) = x_r^2 + y_r^2 - s^2$, notice that $l(x)$ is independent of ϕ_r). Then, for $x_0 \in \Re^n$, $T \geq 0$ and $t \in [0, T]$ define the value function

$$V(x_0, t, T) = \max_{u(\cdot)} \min_{d(\cdot)} l(x(T)) \tag{24}$$

where $x(\cdot)$ is the solution to the differential equation (23) over the interval $[t, T]$ starting at $x(t) = x_0$. Notice that the definition of the value function V assumes that d (the intruder) is trying to minimise the value of $l(x)$ (i.e. make $x_r^2 + y_r^2 < s^2$ and cause a conflict) whereas u (the ownship) is trying to maximise $l(x)$ (i.e. prevent the conflict). The set game winning initial states for the ownship is then the set of x_0 for which $V(x_0, T) \geq 0$ for all $T \geq 0$, i.e.

$$\{x_0 \mid \forall T \geq 0,\ V(x_0, 0, T) \geq 0\}.$$

In equation 24 the min and the max (strictly speaking an inf and a sup) are taken over the space of non-anticipative strategies.

Therefore, if one can compute the function V, one can also determine whether a particular state is safe or not. A standard result in game theory shows that V is a solution (strictly speaking, a viscosity solution) to the Isaacs partial differential equation

$$\frac{\partial V(x, t, T)}{\partial t} + \max_{u} \min_{d} \left(\frac{\partial V(x, t, T)}{\partial x} f(x, u, d) \right) = 0 \tag{25}$$

with terminal condition $V(x, T, T) = l(x)$. Notice that the minimisation and maximisation in equation (25) is pointwise over u and d as real, finite dimensional vectors, whereas the minimisation and maximisation in equation (24) is over $u(\cdot)$ and $d(\cdot)$ as functions of time; the latter are infinite dimensional optimisation problems and are of course much harder.

In principle, if one can solve Isaacs equation then they can also determine the set of states from which a conflict can be avoided. In practice, however, this partial differential equation can be very difficult to solve, especially analytically. Moreover, if u and d have complete control over the angular and linear velocities then a highly complex dog fighting situation results, in which the set of winning states for the ownship is very restricted. To address these problems, two constraints on control inputs are considered in [12]. The first of these is allowing u and d only changes in the angular velocities, ω_1 and ω_2. The second is allowing only changes in the speeds, v_1 and v_2. The boundary of the safe set of initial states in the former case is shown in Figure 11.

A shortcoming of this approach is that it is unduly pessimistic. In practice, commercial aircraft do not seek to minimise separation. A reworking of this theory, using a cooperative approach and safety as an objective may be a focus for further research. A potentially

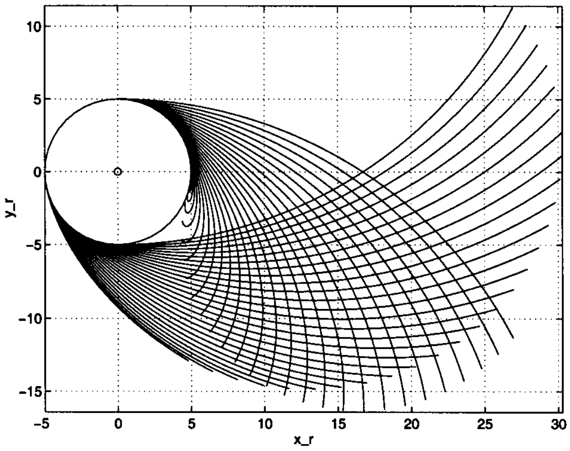

Figure 11: The boundary of the set $Pre_t(T)$ for a variety of values of ϕ_r. [12, Figure 4(b)]

interesting approach is that of [39]. Both cooperative and non-cooperative air traffic management approaches are formulated as dynamic games in [39] and safety is measured in terms of ICAO's metric for collision risk.

5.5 Validation Approaches for CDR Algorithms

Validation is a crucial step in the design of any CDR algorithm. The term validation is used here to refer to all activities whose goal is to demonstrate that the proposed algorithm will work in practice. Common "side-effects" of the validation process include refinement and tuning of the algorithm. Validation frequently exposes flaws in the design process that can be subsequently corrected by the designers. Moreover, CDR algorithms typically involve a number of parameters that can be adjusted to improve the algorithm's performance (e.g. thresholds, approximation bounds, etc.) The validation process provides a way of tuning these parameters to optimise the performance of the algorithm.

Validation can be carried out in three levels of the design process.

Theoretical validation Theoretical arguments can be developed about the ability of the algorithm to predict and/or resolve conflicts. These arguments are typically based on a number of simplifying assumptions about the behaviour of the system. In certain cases the theoretical arguments may be developed with the assistance of automated or semi-automated verification tools, such as model checkers, or theorem provers. Steps in this direction are taken, for example, in [40, 41, 42].

Validation on data Algorithms can be validated by testing their performance on data, either real (e.g. track data), or synthetic (e.g. generated by a simulator). The former approach is taken for example in [18]; the latter in [43]. The relative merits of the two approaches (real vs. synthetic) in the context of the HYBRIDGE study are briefly discussed in Section 4.

Experimental validation Before deployment the algorithms usually need to be tested in practice. This typically involves either human in the loop simulations with realistic air traffic configurations, or field trials. Such a process is currently underway, for example, for the CTAS tools [44]

Within HYBRIDGE algorithm validation will be primarily through theoretical arguments and data; there are currently no plans for experimental validation.

Different aspects of the performance of the algorithms may come under scrutiny during the validation process, including false alarm rates, computational efficiency, human factors issues, etc. For CDR algorithms one the most important is the ability of the algorithm to assess how dangerous a situation is. Different approaches have been proposed in the literature for doing this. The *System Operatic Characteristic* (SOC) approach proposed by [45], for example, measures the performance of the algorithms in terms of trade-off between successful alerts and false alarms. In most of the studies based on this approach validation is done using Monte-Carlo simulation [32, 1]. The algorithm is applied to a large number of simulations of a particular encounter. Probability of successful alert is then defined as

$$P(SA) = \frac{\text{number simulations where an alert was issued before a conflict occurred}}{\text{total number of simulations where conflicts occurred}}.$$

Likewise, the probability of of false alarm is defined as

$$P(FA) = \frac{\text{number of simulations where an alert was issued in the absence of a conflict}}{\text{total number of simulations where conflicts did not occur}}.$$

The SOC curve is a plot of $P(SA)$ vs. $P(FA)$ parametrised by the CDR algorithm parameters (typically the alerting threshold). The SOC curve allows one to investigate the trade-off between $P(SA)$ and $P(FA)$. One can then choose the values of the parameters to optimise this trade-off, or compare the performance of different algorithms in terms of this metric.

The SOC curve relies on the notion of a conflict defined in terms of minimum horizontal and vertical separation standards earlier in this section. It is unclear, however, whether this notion is the best measure of assessing the danger of a particular encounter. Validation can also be carried out, for example, in terms of ICAO's metric of *collision risk* [31, 46]. HYBRIDGE WP2, WP8 and WP9 will continue the study of the application of this metric to advanced operations, under nominal and non-nominal operational situations [34]. However, the collision risk metric may already be quite useful even for the valiadation of CDR algorithms under nominal operational situations.

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A Literature Survey

A.1 Introduction

The following papers have been collected with the objective of identifying safety critical situations and pointing out conflict detection and resolution (CDR) methods in air traffic control. They are divided into two main classes: technical papers and project review papers. Technical papers present more subject specific research. Project review papers describe major European research projects which aim to improve current air traffic control practice.

A.2 Technical Papers

Each paper on this list has been awarded a number of stars, that are meant to reflect roughly its relevance to the HYBRIDGE WP1 effort.

1. **User Manual for the Base of Aircraft Data (BADA) Revision 3.3. *****
   Eurocontrol Experimental Centre [20].
   http://www.eurocontrol.fr/projects/bada/

   Contains detailed instructions on how to access and use BADA, a database of the performance and operating conditions of most commercial aircraft operating over Europe. Details are also provided on the "Total Energy Model" (TEM), which may be used to generate trajectories. The effect of atmospheric conditions on aircraft operation is included. Simple equations for calculating thrust, fuel consumption etc. are given, and standard flight schedules are reported.

2. **A Review of Conflict Detection and Resolution Modeling Methods. *****
   J.K.Kuchar and L.C.Yang [24].
   http://web.mit.edu/jkkuchar/www/pubs.html

   Represents a comprehensive review of current CDR techniques. This paper examined over 60 methods of CDR, classifying them based on the method adopted for predicting the aircraft trajectory (probabilistic, worst case and nominal) and the method used for conflict resolution (prescribed, optimised, force-field or manual). A variety of other distinguishing features is considered. An extensive bibliography is provided, together with an appendix summarising each of the described models.

3. **A Probabilistic Approach to Aircraft Conflict Detection. *****
   M.Prandini, J.Hu, J.Lygeros, and S.Sastry [47].
   IEEE Transactions of Intelligent Transportation Systems, Vol.1, no.4, December 2000

Presents an extensive investigation of 2-D CDR, in the short and mid-range scenarios. An uncertainty model similar to that introduced in paper 10 in this list is used to formulate a conflict detection method, which is implemented using randomized algorithms. A decentralized resolution technique, where each aircraft is responsible for its own flight path, is also proposed. Finally, a comparison between the introduced CD method and CTAS in paper 10 is reported.

4. **A Game Theoretic Approach to Controller Design for Hybrid Systems. *****
   C.J.Tomlin, J.Lygeros, and S.Sastry [25].
   Proceedings of the IEEE, Vol.88, no.7, July 2000.

   Presents a method to design controllers satisfying safety specifications in hybrid systems. Hybrid theory is emphasized and applied to a set of motivating examples, including ATC, where aircraft are modelled as hybrid automata. The conflict free condition is formulated as a reachability problem.

5. **Trajectory Prediction Concepts for Next Generation Air Traffic Management. ****
   A.Warren [29].
   The Boeing Company, CNS/ATM Analysis MS 20-09, PO Box 3707, Seattle, WA, USA.

   Presents a medium term trajectory prediction method, with an emphasis on accuracy and integrity of trajectory predictions for decision support tools. Pays specific attention to prediction errors in climb and descent.

6. **Tactical Conflict Detection and Resolution in a 3-D Airspace. ***
   G.Dowek, A.Geser, and C.Muñoz [17].
   4th USA/Europe Air Traffic Management R&D Seminar Santa Fe, December 3-7 2001.

   Presents a “nominal” model for CDR and investigates necessary conditions for a conflict to occur, based on the intersections between flight paths and the boundaries of the exclusion zones around aircraft. The resulting CDR algorithm solves conflict using a single maneuver by one aircraft, without the collaboration of the others. Simulation results are presented to support the validity of the method.

7. **Trajectory based Air-Traffic Management (TB-ATM) under Weather Uncertainty.**
   A.Nilim, L.El Ghaoui, M.Hansen, and V.Duong [48].

   This is one of the few papers that deals with weather uncertainty, although it considers bad weather to form no-go zones, which must then be avoided. Documentation on the treatment of the effects of weather on flight path errors is very sparse.

8. **Rule Optimization for Airborne Aircraft Separation. ***
   R.Schild [23].
   http://www.eos.tuwien.ac.at/Oeko/RSchild/Rules/id1.htm

   The first sections of this thesis provide a good summary of the current state of Air traffic management and methods of CDR (reproducing a significant amount of [1]). A set of equations describing the motion of a commercial aircraft is provided. They require careful treatment, but may be useful for building a "real world" trajectory simulation.

9. **Geometric and Probabilistic Approaches Towards Conflict Prediction. ****
   G.Bakker, H.Kremer, and H.Blom [46].
   National Aerospace Laboratory NLR, PO Box 90502 1006 BM Amsterdam, The Netherlands.

   Considers four CD approaches, a classical geometric (nominal) method and three probabilistic methods one of which is original. The three 'standard' approaches are considered and briefly reviewed, while the novel approach is more thoroughly investigated.

10. **Conflict detection and resolution in the presence of prediction error. *****
    H.Erzberger, R.Paielli, D.Isaacson, and M.Eshow [26].
    http://www.ctas.arc.nasa.gov/publications/papers/

    Papers by the first two authors are heavily referenced by other authors. This paper, and the next three in this list detail the work performed at NASA to develop CTAS (Centre TRACON Automation System), and summarise the CDR methods currently in use. The complete CTAS model is detailed and typical conflict probability graphs are shown.

11. **Conflict Probability Estimation for Free Flight. *****
    H.Erzberger and R.Paielli, [27], see also [49].
    http://www.ctas.arc.nasa.gov/publications/papers/

    Similar coverage to item 10.

12. **Conflict Probability Estimation Generalized to Non-Level Flight. *****
    H.Erzberger and R.Paielli [38].
    http://www.ctas.arc.nasa.gov/publications/papers/

    A generalization of the approach of items 10 and 11 to non-level flight.

13. **Empirical Test of Conflict Probability Estimation. ****
    R.Paielli [18].
    http://www.ctas.arc.nasa.gov/publications/papers/

An approach to the validation of the probabilistic prediction model used in items 10-12 based on track data.

14. **PHARE Highly Interactive Problem Solver (HIPS).**
    Eurocontrol Experimental Centre [6].

    Describes a complete system for ATM. HIPS combines a novel approach for the display of air situations with a trajectory editor to give a rapid and reliable tool for planning aircraft trajectories, and resolving conflicts between aircraft. Based on trajectory information HIPS produces a plot of the airspace, highlighting "no go zones", in which loss of separation would be expected. Routing all planes such that they do not enter the no go zones ensures safe routing. This solver is based principally around a "nominal trajectory model".

15. **Conflict Resolution for Air Traffic Management: a Case Study in Multi-Agent Hybrid Systems. ****
    C.Tomlin, G.Pappas, and S.Sastry [12].
    Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, Berkeley, CA 94720

    Introduces the use of hybrid systems for developing effective conflict resolution algorithms. A game theoretic approach is used, in which an uncooperative 'intruder' aircraft is considered as a disturbance, and an optimal control for the 'ownship' is found such that conflict is avoided. The output of this method is a set of initial states from which conflict cannot arise given a particular control strategy.

16. **Multi-objective Hybrid Controller Synthesis.**
    J.Lygeros, C.Tomlin, and S.Sastry.
    Laboratory for Computer Science MIT, NE43-374, 545 Technology Square, Cambridge, MA 02139

    Describes the problem of synthesizing hybrid controllers which satisfy multiple control objectives. Optimal control techniques are used to determine the class of least restrictive controllers that satisfies a certain critical objective (referred to as safety). Further performance objectives can then be optimized within this class of controllers. The proposed technique is illustrated on ATM examples.

17. **Hybrid Control in Air Traffic Management Systems. ***
    S.Sastry, G.Meyer, C.Tomlin, J.Lygeros, D.Godbole, and G.Pappas.
    Intelligent Machines and Robotics Laboratory,Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720-1770

    Presents an architecture for an automated ATMS with decentralized control, with the free flight concept applied outside the TRACON region. Different types of conflicts that may occur in this architecture are discussed, as well as methods of resolution and trajectory planning.

These papers constitute a fairly comprehensive overview of existing CDR methods. Conflict prediction based on nominal trajectories is a widely studied area, and most of the current work in this field revolves around effective implementation of the achieved results, and improving Human Machine Interfaces (HMIs). Research on probabilistic methods is less complete; uncertainty models are generally quite simple, typically based on the description of the aircraft position as a Gaussian random variable. Although crucial for a realistic trajectory modelling, the effect of wind is neglected. This is perhaps due to the lack of accurate wind data, and the limited information on its effect on aircraft trajectories.

A.3 ATM Projects

Out of the many rsearch projects on ATM funded by the European Commission, Eurocontrol, etc. we list below a few, which in our opinion are most closely related to the CDR activities on HYBRIDGE.

18. **MA-AFAS. More Autonomous - Aircraft in the Future Air Traffic Management System.**
    htt://www.ma-afas.com/

    Aims to transform ATM research results into practical operational procedures, giving substantial near term ATM improvements. The Operational Concepts common between MA-AFAS and AFAS are described. Uses the TORCH framework of paper 20 in this list to build the MA-AFAS concept. In progress, projected completion in 2005.

19. **AFAS. Aircraft in the Future Air Traffic Management System.**
    http://www.euroafas.com/afas/

    Defines the operational environment characteristics of the AFAS GATE-TO-GATE concept. This concept focuses on efficiency and capacity enhancements within a short term horizon, while maintaining or improving safety. It also paves the way for further long-term future enhancements. The two main elements of AFAS are time based ATM and dissemination of accurate 4-D trajectories from the aircraft to the ground to enable more effective time based ATM. In progress, projected completion in 2005.

20. **TORCH - Technical, EcOnomical and OpeRational Assessment of an ATM Concept AcHievable from the year 2005.**
    Internal only.

Describes the TORCH operational concept proposed to solve the current ATM problems in Europe in the areas of capacity, safety, flexibility and efficiency. Each element and its related functions and services is described. The document also identifies potential changes, potential overall benefits and specific socio-economic benefit mechanisms which the elements may produce. In progress, projected completion in 2005.

21. **ISAWARE - Final Synthesis Report.**
Thales-Avionics.
http://www.nlr.nl/public/hosted-sites/intent/intent.htm

    The main aim of ISAWARE is to improve flight safety by providing the pilot with a complete predictive situation awareness during all phases of flight. The key concept within ISAWARE is ISAS - Integrated Situation Awareness System, which aims at providing flight crews with perception of their operational environment. The two focus areas of ISAWARE are increased logic algorithm performance and enhancement of the Human Machine Interface (HMI). Completed, final report issued on 30/11/2001.

22. **INTENT - The Transition towards Global Air and Ground Collaboration in Traffic Separation Assurance.**
http://www.nlr.nl/public/hosted-sites/intent/intent.htm

    INTENT contributes to the work programme for Competitive and Sustainable Growth of the European Union. Specifically working on 'Improving operational capability and safety of aircraft', and 'air traffic management related airborne systems'. In progress, projected completion 12/2002.

23. **ARAMIS - Advanced Runway Arrivals Management to Improve airport Safety and efficiency.**
http://cordis.lu/transport/src/aramisrep.htm

    The global goal of this project is to adapt and develop models and tools for 4D-planning, guidance and control during the approach phase of flight. Completed, April 1998.

24. **FARADEX - Functional Architecture Reference for ATM Systems and Data EXchange.**
http://www.cordis.lu/transport/src/faradex.htm

    This study defines the functional architecture of overall ATM systems. The main aims, amongst others, are to:

    - Consolidate existing state of the art materials relevant to functional architecture.

- Form a reference to be used as a basis for advanced ATM systems.
- Provide a common view of the ATM system functional architecture.
- Serve the EATCHIP / EATMS programme.

Completed, 01/01/1998.

25. **Single European Sky. European Commission Directorate General for Energy and Transport.**
    http://europa.eu.int/comm/transport/themes/air/english/single_eur_sky_en.html

    Report of the recommendations of the European Commission High Level Group, setting out the current problems in European ATM, and proposing the development of a Single European Sky concept - a seamless ATM system across Europe. The changes required to achieve this are presented, and conclusions and recommendations for further work are presented. In progres. Final report 2000, projected implementation 31/12/2004.

26. **RHEA - Role of the Human in the Evolution of ATM Systems. 1996-1998**
    http://www.cordis.lu/transport/src/rhearep.htm

    A report on a project assessing the importance of human factors in the air traffic control. The main aim is to set out a plan for the evolution of ATM such that unsuitable automation concepts and systems could are not implemented in the future. Completed, final report issued 1998.