Exploring Opportunities for an Evolutionary Integration of Level 3 UAV Situation Awareness Support into ATC/C2 systems

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Master of Science Thesis



Exploring Opportunities for an Evolutionary Integration of Level 3 UAV Situation Awareness Support into ATC/C2 systems

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For the degree of Master of Science in Electrical Engineering, track Telecommunications at Delft University of Technology

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Abstract

An Unmanned Aerial Vehicle (UAV) is an aircraft controlled by a pilot who is not physically on board, but situated in a so-called UAV control station (UCS). Until today, military UAVs have flown in segregated airspace for training purposes. Also, they have flown missions in many war zones. However, it is today not possible for UAVs to normally operate in non-segregated airspace. In order to integrate UAVs in non-segregated airspace, as a first step effort is needed on several regulatory and technology issues. To overcome technology issues, a joint research project between Delft University of Technology (DUT), the Royal Netherlands Air Force (RNLAF) and The Royal Netherlands Naval College addressed several aspects of UAV airspace integration. One of the developments has been conflict probing, which supports UAV operators to obtain level 3 situation awareness¹. Conflict probing supports UAV operators with a better conflict detection capability, and with a limited false alarm rate. Obtaining level 3 situation awareness is also a fundamental need for safe and efficient Air Traffic Control (ATC) and Command and Control (C2). Uncommon UAV missions types and uncommon flight dynamics, demand additional effort of air traffic controllers. Conflict probing might compensate for this additional effort in a different way, with hands on information about the areas where a loss of separation occurs that can directly support a controller with his separation task.

Objectives on airspace integration in Air Traffic Management strategies like NextGen and SESAR are very high-level and long-term, whereof no delays are considered yet. In the strategies no intermediate solutions are foreseen for connectivity. However, waiting until the promised connectivity is there, will unnecessarily delay the moment at which significant operational gains in predictability can be realized. Hence, the objective of this thesis is to provide ATC with support for level 3 UAV situation awareness. Therefore, the potential of conflict probing for ATC is explored. Exploiting near-term opportunities in the area of connectivity, data integration and data presentation, conflict probing is demonstrated on an existing ATC system.

¹M.R. Endsley defined situation awareness in three levels: 'The perception of the elements in the environment with a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future'.

To explore this question and its near-term technical feasibility, an identification and analysis of possibilities to add the conflict probing function to an existing ATC system, the Multi-Aegis Site Emulator (MASE), was performed. In an ATC application, different surveillance sensors are used. For conflict probing, demanding requirements are imposed on position and velocity accuracy. To assess whether the available data meets these requirements, an extensive feasibility analysis is performed on radar surveillance accuracies in many conditions.

For the implementation, a system-independent platform is designed with connectivity and data presentation designed independently from the MASE. The proposed system architecture comprises a separate, stand-alone computer which captures the ATC display in real-time and uses a video overlay to add the conflict probes. To compute the location of the conflict areas, a real-time feed of track information is required. For this, a real-time feed of track information is required, which was available in Eurocontrolts ASTERIX standard at the Royal Netherlands Air Force Air Operations Control Station Nieuw Milligen.

In essence, a platform is created to test innovative ATC/C2 concepts with no impact on the operational environment. In the feasibility study accuracies vary greatly. Holding on to the worst-case accuracy leads to infeasible conflict probing. With a dynamic conflict zone accuracy, based on actual surveillance sensor performance, for those situations that exceed the worst-case assumption, the false alarm rate is reduced. The DUT research UCS, MASE and the implementation platform are successfully tested together for three major support functions on several realistic scenarios in a recorded Dutch air picture. With the concept demonstrator, it is illustrated that TRL 6 is reached.

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Right after I had entered my Master's degree with Telecommunications, I was affected by the Avionics group. In the years before, spectacular excursions were organized to Amsterdam Airport Schiphol and to NATO airbase Geilenkirchen. In the second year, after the real flight every student of the Avionics course Airplane Performance was offered, I was convinced of ATM and applied for an internship at Luchtverkeersleiding Nederland. My enthousiasm did not change when the Master's thesis came into play. Erik and myself found out that a mix of Air Traffic Management and UAV airspace integration would be both relevant and interesting. This document describes the final results of this study.

Before guiding you into the complex world of ATM, I would like to thank some driving forces. First of all, I am thankful to Erik Theunissen as the devoted power behind the Avionics group. His creativity and criticism have definitely made me a better engineer. Furthermore, his programming skills enabled for the ATC video overlay. Secondly, I am grateful to Joris Koeners. We have worked out the integration platform for the surveillance data processing and MASE presentation together. I will not forget the unbounded discussions on the long roads to Nieuw Milligen. That brings me to Jan Tanis and Lenette Meijer and many others of the Air Operations Control Station Nieuw Milligen who facilitated this project greatly, we could not have realized this demonstrator without them.

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Chapter 1

Introduction to UAV developments

An Unmanned Aerial Vehicle (UAV), or an Unmanned Aircraft System (UAS), is an aircraft controlled by a pilot who is not physically on board, but situated in a so-called UAV Control Station (UCS). In the seventies, major technological advances were made in UAV research. Soon, the first UAV with surveillance capabilities was introduced in the Vietnam war [1]. Thereupon, UAVs have acquired a prominent role in warfare. In the last decade, UAVs have flown almost 500,000 flight hours in support of Operation Enduring Freedom in Afghanistan and Iraqi Freedom in Iraq [2].

The tasks they perform in war are reconnaissance, surveillance, target identification and more often strike missions. With UAVs added to the arsenal, the military acquires the ability to operate in high threat environments without putting warfighters at risk. This is not only safer, but potentially also more effective [3].

While most knowledge is with the military, more and more civil initiatives arise. For instance, UAVs can play an important role in remote sensing of the environment, geographic surveys, border patrol, transport of goods, and search and rescue. Today, over 32 countries are developing UAVs. The most sophisticated military systems are designed by the United States (US) and Israel, while Japan has the most UAVs in operation for agricultural spraying [4].

The UAV and the UCS communicate over a datalink, either over a radio connection or via a satellite relay. If the connection with the UAV is lost, technology exist to autonomously continue the mission or safely land the aircraft flying a pre-determined trajectory back to the airbase. UAV developments in the last decades have enabled these autonomous operations. Although autonomy will increase, humans will always intervene to provide high-level objectives, set rules of engagement, supply operational constraints, and support launch-andrecovery operations from the ground [2].

It is today not possible for UAVs to normally operate in non-segregated airspace, while there is a clear need. In order to integrate UAVs in non-segregated airspace, effort is needed on several regulatory and technology issues. The US and Europe work jointly on standardized UAV airspace integration regulations with their respective Air Traffic Management (ATM) strategies. To give an understanding of the background of this study, the next two sections describe the challenges in airspace integration and the developments in ATM strategies. After that, the objective and scope of this thesis is explained. Then, common definitions are provided, followed by the report structure.

1-1 Airspace integration

For a long time, military UAVs have flown in restricted airspace for training purposes. In the meantime, UAVs have flown missions in many war zones. In order to integrate UAVs in non-segregated airspace, effort is needed on several regulatory and technology issues. Both types of issues are explained.

The most relevant regulatory issue is airworthiness certification. Current UAVs have different capabilities than manned aircraft. Hence, they do not fit current classification schemes in airworthiness certification. There are a variety of classification schemes for UAVs, like schemes based on operating altitudes, operational characteristics, mass and speed. None of these have been adopted by the aviation authorities yet. In the US, a UAV considering a flight in national airspace still needs individual approval. This approval process, known as a Certificate of Authorization (COA) and contained in the Federal Aviation Administration (FAA) Order 7610.4, requires the case-by-case safety evaluation of each flight [4]. The approval process can take weeks to months depending on the FAA region or regions where the flight will take place. If the UAV goes beyond visual range, a chase plane is required to keep visual on the UAV at all time. Furthermore, Europe, the United Kingdom, France and Sweden have national regulations which all state that UAVs are currently not allowed to operate outside segregated airspace [5].

Currently, several North-American and European efforts, the most important being the JAA/Eurocontrol UAV Task Force, are put into the development of regulations. In February 2012, US President Obama signed the FAA Modernization and Reform Act 2012 - with funding and provisions for granting military, commercial, and privately-owned UAVs greater access to U.S. airspace and air traffic management systems modernization - into law. The US Congress set a 30 September 2015 deadline for full integration of UAV into the US national airspace [6].

The main technology issue is related to the definition of the see-and-avoid requirement in manned aircraft, that cannot be applied to the UAV counterpart. See-and-avoid partly relies on the human eye, for instance, detecting traffic and compliance monitoring of the runway location through the cockpit window. In turn, Detect, Sense and Avoid (DSA) functions can enable a UAV to respond autonomously and safely to a collision threat in a manner equivalent to pilots of manned aircraft. However, current technology in manned aircraft is limited, e.g. using Traffic Collision Avoidance System (TCAS) II for self-separation is considered unsafe in a UAV [7].

Historically, UAVs have a poor safety record compared to manned aircraft. Generally, this comparison is not always fair, since until now most UAV operations have been experimental. Moreover, they have taken place in high risk environments. Furthermore, UAVs have not had the operational support manned aircraft are used to. This paradigm is changing now flight hours have increased rapidly and technologies have improved. UAV reliability, depending on type of aircraft, is approaching the level of manned military aircraft [2]. Because of the

different nature of the system and its history, it remains hard to empirically demonstrate that the systems have equivalent levels of safety.

In this thesis UAV airspace integration is studied from the perspective of ATC. The most relevant differences between manned and unmanned aircraft for ATC are identified as:

- The navigation system of a UAV has a higher level of system autonomy and authority than that of a manned aircraft;
- A UAV may be equipped with an autonomous conflict prevention system with different levels of operator involvement;
- A UAV should be equipped with an autonomous collision avoidance function to maneuver in case of a lost link and a collision hazard;
- ATC voice communication to a UAV is relayed to the UCS and vice versa;
- A UAV is deployed for unique, enduring, recurring missions;
- A UAV has different flight dynamics than most commercial aircraft.

The unique mission types and unique flight performance make anticipation on UAVs initially harder. The limited predictability of future separation between UAV and traffic increases ATC workload, what results in larger separation margins for UAVs in an experimental stage. In the long run, larger separation margins may impact airspace efficiency. To further compensate for the controller's reduced future conflict awareness, ATM strategies plan to interconnect systems to share relevant information.

1-2 ATM strategies

Future ATM concepts aim to achieve a seamless integration of unmanned aircraft in nonsegregated airspace by increasing predictability through interconnecting systems over a secure communication network to get the right information at the right place at the right time. Network-Enabled Capability is the military information sharing theory, while in civil aviation, System Wide Information Management (SWIM) is the plan for securely connecting all the ATM stakeholders to share data.

The Single European Sky ATM Research (SESAR) and the Next Generation Air Transportation System (NextGen), written by respectively Eurocontrol and the FAA, are such plans that embraced SWIM [8, 9]. The plans furthermore describe the whole transformation from state-based operations to trajectory-based operations, where trajectories are beforehand deconflicted to support a larger volume of aircraft more efficiently. 4D-Trajectory (4DT) management over datalinks is further described in Subsection 2-2-2. In these plans, more accurate surveillance data is provided by Automatic Dependent Surveillance-Broadcast (ADS-B), further described in Subsection 2-2-1. UAV airspace integration was not among the original goals of the plans, however, enhanced surveillance data and digital data links, facilitate the mix of manned and unmanned aircraft.

SESAR and NextGen are strategic plans, developed by respectively Eurocontrol and the FAA. These plans represent their early view on what future ATM should look like. In these plans no objective is extensively described. SESAR describes five consecutive levels with individual time lines up to at least 2025. NextGen imposes no time constraints in its vision on ATM, other than the aspiration to finish before 2025. Both mean that when realizing objectives, complexity and costs might increase, resulting in delays likely up to years, not to forget about changing plans. There is a significant time span from now until the first deliverables come available.

1-3 Objective and scope

Today's Air Traffic Control (ATC) and Command and Control (C2) have not been designed with SWIM-based capabilities. Although global strategies aim to achieve coordination and synchronization between UCS and other systems, the UCS also lacks the ability of sharing information widely.

Yet, the UCS has a lot of information available, of which some are received over the datalink with the UAV. For instance, accurate UAV state information is downlinked to the ground. Also, the UAV trajectory is controlled from the ground. Opportunities exist for best-effort information sharing, based on current enabling technologies. The capabilities of systems retrofitted with networking capabilities are limited. However, waiting with the implementation until the promised connectivity is there, unnecessary delays the moment at which significant operational gains in predictability can be realized [10].

Since 2001, a joint research project between Delft University of Technology (DUT), the Royal Netherlands Air Force (RNLAF) and The Royal Netherlands Naval College has addressed several aspects of UAV mission management and airspace integration. One of the developments is conflict probing, which is defined as predicting the future separation between ownship and intruders for a set of ownship velocity vectors - representing possible combinations of track, flight path angle and velocity [11]. Conflict probing supports UAV operators to obtain level 3 situation awareness¹ with a better conflict detection capability, and with a limited false alarm rate.

Obtaining level 3 situation awareness is also a fundamental need for safe and efficient ATC. Uncommon UAV mission types and uncommon flight dynamics, demand additional effort of air traffic controllers². Conflict probing might compensate for this additional effort in a different way. With conflict probing, no external information is involved. Conflict probing involves the yet available state information and presents a spatially integrated depiction of areas to avoid. This hands on information about the areas where a loss of separation occurs can directly support a controller with his separation task. Moreover, when in an experimental stage additional separation margins are used, these can also be monitored closely with the conflict probing concept can aid a controller with the limited UAV predictability.

In subsection 1-1 the differences between manned and unmanned aircraft for ATC were identified and listed. Generally, differences cause complications. Here, opportunities exist to

¹M.R. Endsley defined situation awareness in three levels: 'The perception of the elements in the environment with a volume of time and space (level 1), the comprehension of their meaning (level 2), and the projection of their status in the near future (level 3)'.

 $^{^{2}}$ Air traffic controller is abbreviated to controller, while UAV operator is abbreviated to operator.

benefit from these dissimilarities. In the next subsection differences and their impact, and opportunities and challenges are studied. Afterwards, the goal of this thesis is defined.

1-3-1 Differences and impact

The main differences in the implementation of UAV related functions in an ATC environment are:

- The computational load of the conflict probing algorithm increases significantly with the number of aircraft involved, hence, the performance of conflict probing applied to all aircraft is limited [12];
- Sensor accuracies are found to be a main contributor to the size of conflict areas [13]. ATC's surveillance accuracies are expected to be worse than ADS-B accuracies;
- Reference and orientation of the ATC screen are not ownship-referenced, as is the case in a Navigation Display (ND). Therefore, aircraft identification for conflict probing in busy airspace might be hard;
- The target ATC/C2 system, the Multi-Aegis Site Emulator (MASE), is a legacy system where modifications are hardly supported [10]. An integration into an ATC/C2 system is harder than into the DUT research UCS.

As more aircraft are involved and worse sensor accuracies are available, this might result in clutter. The role of ATC is to safely and efficient control all traffic. Large conflict areas are disturbing and provide inadequate information. At a first glance, the concept seems not very useful for ATC. The high computational load, and the lack of integration options, also make conflict probing for ATC technically hard to realize.

1-3-2 Opportunities and challenges

Opportunities exist to benefit from the differences listed. When conflict probing is applied from many to many aircraft, the performance requirements increase with a power of two, because any aircraft now probes any aircraft. However, it is stated before that the UAV is an unconventional aircraft that demands additional controller effort, at least in an experimental stage. Conflict probes are introduced particularly to compensate for the limited predictability of future separation with the UAV. When conflict probing is applied to a UAV particularly, the computational load and clutter are not different from the implementation in a ND.

Although ATC surveillance accuracies are expected to be worse than ADS-B accuracies, opportunities with radar surveillance exist. ATC radars are accompanied by a radar tracker, which associates subsequent radar plots into tracks. Moreover, a radar tracker applies algorithms for state-estimation to further improve the accuracy of state information. State-estimators also determine their own estimation accuracies with each individual track update. These accuracies provide ATC with actual surveillance sensor performance, instead of the rough performance levels transmitted with ADS-B. This gives an opportunity for a more realistic conflict assessment, and the use of dynamic look-ahead times depending on the actual surveillance sensor performance.

The conflict probe depiction for ATC requires conformal mapping of information on the ATC/C2 system. It does not necessarily requires a full integration into the system. The

data of the MASE and the UAV support can also be mixed on the video level. This video overlay concept is the opportunity of presenting all information on the same screen, with no constraints in programming language, security classifications and costs.

The opportunities briefly demonstrate the potential of an explorative study into ATC support for level 3 UAV situation awareness. Next, the objective of this thesis is stated.

1-3-3 Objective of this thesis

The goal of this thesis is for the demonstrator subdivided into the three relevant areas connectivity, data integration and data presentation:

To provide ATC with support for level 3 UAV situation awareness, the potential of conflict probing is explored. Exploiting near-term opportunities in the area of connectivity, data integration and data presentation, conflict probing is demonstrated on an existing ATC system.

This study aims to realize a system with a high Technology Readiness Level (TRL). TRL is a measure used by some agencies around the world to rate the maturity of evolving technologies. The US Department of Defense defines TRL 6 as a system/subsystem prototype demonstrator in a relevant environment [14]. TRL 5, defines only a component validation. TRL 7, on the other hand, is a system/subsystem prototype demonstrator in an operational environment. In this study, TRL 6 will be the limit, since the final goal is a concept demonstrator, which will not be tested extensively in an operational environment.

1-3-4 Problems

From the objective of this thesis, four relevant questions regarding constraints are identified and addressed:

- How can conflict probing be implemented in an ATC environment with no restrictions to the operational environment?
- How can the conflict probing algorithm be supplied with its required parameters?
- How do ATC surveillance sensor accuracies affect conflict probing for ATC?
- How can a conformally integrated display concept be realized?

1-4 Definitions

To make a clear distinction between different concepts in situation awareness and conflict scenarios, the most relevant concepts are defined in this section.

Within situation awareness, the following three concepts are distinguished: traffic awareness, future conflict awareness and conflict awareness. The threesome is classified into three awareness levels: detection, integration and anticipation. Obviously, the higher goal to provide support for traffic awareness is to prevent conflicts. For conflicts specifically, a distinction in phase is made between the situation where a conflict exists, and the situation prior to

Awareness level	Conflict phase: Traffic awareness	Future Predictive conflict awareness	Current Conflict aware- ness
1-Detection	Aware that there is traffic	Aware that a conflict will occur	Aware of the exis- tence of a conflict
2-Integration	Aware of the relative location of traffic	Aware where and when the conflict will occur	Aware of the loca- tion/extent of the conflict
3-Anticipation	Aware of the fu- ture location of traf- fic (relative to own- ship future location)	Aware of how a change to the cur- rent state will affect the time and loca- tion of the conflict. Also proximity (not on current track)	Aware how a change to the current state will allow the separa- tion to be regained

Table 1-1: Traffic and current and future conflict awareness expressed in three awareness levels.

a conflict. An overview is provided in Table 1-1, with horizontally the conflict phase and vertically the awareness level.

Comparatively, the consistency in the definition of DSA functions is rather confusing. For the uniform use in this research, a brief definition of all different functions is given here.

Conflict prediction - the ability of predicting whether the current track of ownship will lead to a future conflict situation with the track of another aircraft;

Conflict prevention - the ability to timely determine appropriate action to avoid a conflict situation;

Conflict detection - the ability to detect a conflict situation, i.e. a loss of separation already occurred;

Conflict resolution - the ability to resolve a conflict situation with appropriate actions, and regain separation;

Collision avoidance - the ability to avoid a collision with another aircraft after separation is lost, and the last resort is an immediately initiated avoidance maneuver.

In the remainder of this research, these definitions are applied consistently. In the next chapters limited attention is paid to concept definition.

1-5 Report structure

This report has the following structure. Chapter 1 described the background, the relevance of the research and the objective and scope of the research. Chapter 2 explores opportunities

in information sharing with the UCS and the application of a conflict prediction concept from literature. Next, Chapter 3 describes the requirements for a design and implementation of ATC support. Chapter 4 describes the analysis of data quality, and based on the results, enhancements to the conflict probing concept. The design and implementation of support into a real ATC system is described in Chapter 5, after which testing and demonstration is described in Chapter 6. The report ends with Chapter 7: conclusions and recommendations.

Chapter 2

Near-term opportunities in technology

In this chapter the near-opportunities in technology, as highlighted in Chapter 1, are studied. ATC already has many tools available to handle aircraft of which three are mentioned. Firstly, the primary surveillance radar, developed in World War II. This radar operates independently of the target aircraft - no action is required to provide a radar return. Secondly, the secondary surveillance radar, which interrogates the aircraft's transponder. In turn, the aircraft transponder responds with relevant information about e.g. altitude and flight identification. The secondary surveillance radar is dependent on the cooperation of the aircraft. For this reason, primary and secondary surveillance radars are usually collocated to get a complete airspace picture. Thirdly, all aircraft provide ATC with flight plan information what is centrally processed for correlation and scheduling.

All of this information supports the controller with his task "to separate aircraft to prevent conflicts, to organize and expedite the flow of traffic, and to provide information and other support for pilots when able [15]". ATC's current toolset supports the controller with level 2 traffic awareness, where the controller is aware of traffic and aware of the relative location of traffic. Level 3 traffic awareness is limited, and only based on the controller's mental ability to extrapolate the current traffic's location into the future. This level of awareness is even harder to achieve when the controller is unfamiliar with the type of aircraft, and particularly its speed. Conflict predictors can assist to obtain level 3 future conflict awareness, presenting not only information about when a where a conflict will occur, also how a change of current state will prevent the conflict.

The next section explains the rationale behind separation margins, a fundamental concept in this study about increasing predictability. After the discussion of separation margins, the opportunities of sharing information between UCS and ATC are explored, and whether it is feasible to share this information in the near-term with enabling technology. Furthermore, the opportunities of conflict prediction for ATC are described. The chapter ends with concluding remarks.

2-1 Separation margins

Separation is the concept of keeping an aircraft outside a minimum distance from another aircraft to reduce the risk of those aircraft colliding, as well as to prevent accidents due to wake turbulence. Controllers apply rules to guarantee the are well clear from each other. Aircraft to which these rules have been successfully applied, are said to be separated, the risk is in control. If separation is lost between two aircraft, they are said to be in a conflict situation. In radar separation, a controller observes the two aircraft are on a minimum horizontal and vertical distance from each other. The by law enforced separation minima are in this research called the Assured Nominal Separation Distance (ANSD). The FAA rules specify [15]:

- 1. Less than 40 NM from the radar antenna, horizontal separation is 3 NM from obstructions or other aircraft.
- 2. 40 NM or more from the radar antenna, horizontal separation is 5 NM from obstructions or other aircraft.
- 3. Up to and including FL 410, vertical separation is 1,000 feet.

Separation margins have two goals: providing sufficient spacial and temporal margin to restore separation when it has been lost. Furthermore, to account for uncertainty in current and future position data (sensor accuracies, limitations of the extrapolation model, pilot/automation actions other than expected [16]). It is assumed that sensor inaccuracies are the main contributor. The FAA rules listed imply that radar inaccuracy generally accounts for at least 2 NM. Thompson [17] justifies this assumption. Perhaps, different ATC procedures also play a role here.

Sensor accuracies play a dominant role in the prediction of future separation. If conflict prediction is applied in an ATC environment, different sensors and different sensor accuracies are considered. To get an understanding of what and how sensor accuracies contribute to current and future aircraft position, the contribution is explained for radar accuracies. Additionally, the introduced estimation errors of a radar tracker are described. Finally, in conflict prediction, accuracies have an accumulated effect. It is therefore relevant to involve prediction inaccuracies into the discussion.

2-1-1 Radar accuracies

Rotating ATC/C2 radars determine aircraft range with the time the electromagnetic signal takes to return to the antenna as echo. The azimuth determination of the target is determined by the direction in which the antenna points when the echo is received. Radar range and azimuth both have limited accuracy. The range accuracy is primarily determined by the timing in the electronics. The azimuth accuracy is mainly influenced by the directivity of the antenna and the velocity of the radar platform.

2-1-2 Radar tracker accuracies

The role of the radar tracker is to monitor consecutive updates and determine those sequences of echos belonging to the same target, named a track. A tracker can use multi-radar input to maintain a track. For each track, the radar tracker uses algorithms to estimate current

Look-ahead time (s)	Future position accuracy (m)
0	100
5	150
10	200
30	400
60	700
120	1300
180	1900

 Table 2-1: The accumulated effect of position accuracy, and velocity accuracy over the lookahead time.

velocity and heading, based on current and past position information. Velocity can only be extracted by a Doppler radar. Making use of the derivative of position data, the radar tracker can also obtain velocity. In turn, heading is determined as the direction of the velocity vector.

For radar trackers algorithms exist to smoothen radar tracks, e.g. Kalman filters or particle filters. Before a track is updated with the latest plot, the tracker algorithm estimates a new position based on the most recent state estimate (position, heading, velocity, acceleration). In this estimation, the current mode of operation is taken into account, e.g. whether the aircraft has constant velocity, is flying level or is in a turn. Next, the latest track prediction is combined with the latest plot to provide a new estimate of the target state, as well as a revised estimate of the errors in this prediction. The radar tracker registers the estimated accuracies of, e.g. position, velocity and altitude in track information.

2-1-3 Prediction accuracies

A predictor projects aircraft positions into the future. A conflict predictor also determines future separation, based on the ANSD. From the radar and radar tracker accuracies subsection, it is explained that position and velocity are estimations with limited accuracies. In predictions, these accuracies show an accumulated effect.

In the determination of future position, the current position with a certain position accuracy, is the initial reference. Velocity and velocity accuracy perform the translation from current to future position, where every second the position is extrapolated with the velocity vector. Simultaneously, the future position accuracy decreases with the velocity accuracy. A simple example of the future position accuracy for different look-ahead times is shown in Table 2-1, where the position accuracy is 100 m, and the velocity accuracy is 10 m/s. In essence, prediction accuracy is the accumulated effect of position accuracy, and velocity accuracy over the look-ahead time.

2-2 Sharing information between UCS and ATC

The quality of a prediction as explained in subsection 2-1-3 strongly depends on two aspects; the accuracy of state information and the availability of intent information. As described in Subsection 2-1-3, state information, in terms of position and velocity, accounts for the prediction accuracy when the current state is maintained. As every aircraft changes track eventually, the validity of a state-based prediction is limited. Intent information, e.g. in

terms of the UAV trajectory, provides information about the planned future position. State information and trajectory information can be summarized as:

State information - The aircraft's state is its condition at a particular time, in ATC usually expressed in geographic position, indicated airspeed, pressure altitude and track.

Trajectory information - A precise description of an aircraft's path in space : the centerline of a path plus the position uncertainty, using waypoints to describe specific steps along the path [9]. In 4DTs the planned trajectory is an *agreement* including time constraints. In a simpler 3D trajectory environment the spatial path is agreed, while the time aspect is only a *planning*.

For both types of information, the current operation is described with the identified deficiencies in the disconnected situation. Then, the opportunities are highlighted with enablers in case of connectivity.

2-2-1 State information

Geographic position, velocity, altitude and track are required parameters for conflict prediction. ATC extracts these parameters for all traffic in range from their surveillance radars. The UCS gets this information about ownship downlinked from the datalink with the UAV. Most UAVs use a Global Satellite Navigation System (GNSS), mainly to determine the position of the UAV, but it is also used for other purposes, e.g. attitude determination, relative positioning [18].

Identified deficiencies

Currently, the UCS has a lack of redundancy in state acquisition for a lost link situation. ATC, in turn, has limited accuracy compared to the UCS.

Opportunities

The exchange of state information is relevant to monitor conformance. In event of a lost link, the UCS completely loses track of the UAV. In that case, ATC has the opportunity to relay state information to the UCS [19]. The UCS then assesses whether the UAV adheres to the preprogrammed route. ATC, in close contact, monitors and ensures that the UAV stays free of conflicts. With more accurate state information with ATC, extrapolations for level 3 (future) conflict awareness are computed more accurately. Next to that, ATC benefits from an improved update rate, which results in an increased predictability on low-speed, turn-intensive trajectories.

Enabling technologies

Automatic Dependent Surveillance-Broadcast (ADS-B) is a surveillance technology for tracking aircraft [9]. ADS-B equipped aircraft are able to broadcast position, altitude and airspeed, which can be received by ground stations and ADS-B-in enabled aircraft. Position information is determined using GPS. ADS-B will be deployed in Europe as an extension to the normal Mode S transponder [20]. By using Mode S technology, the compatibility with current secondary surveillance technology is maintained, although the transponder no longer has to be interrogated. ADS-B is mandated in Europe from 2015, while in the U.S. not before 2020 [21].

The implementation of ADS-B can provide ATC with a higher accuracy of position and velocity information. More accurate position and velocity information increases aircraft predictability, since prediction accuracy strongly depends on the current position and velocity accuracy. For the coming years, it is expected that Air Navigation Service Providers will hold on to their surveillance radar although ADS-B infrastructure is almost deployed in the course of the ADS-B mandate. However, it is not expected that a mixed equipage of ADS-B and surveillance radar will be operational before this mandate.

So, there is not a strategic message format to facilitate state information exchange in the near-term. Therefore, state information exchange is not considered for implementation at this stage.

2-2-2 Trajectory information

Trajectory-based operations (TBO) are not supported in ATM yet. TBO are one of the fundamentals being developed by SESAR and NextGen. They are supposed to be implemented after 2020 [8, 9]. Most UAVs operate on a loaded or an uplinked trajectory. The loaded and uplinked trajectory show similarities with TBO. In the UCS, a trajectory is created and adjusted. The new trajectory only becomes active after it has been successfully received by the UAV. However, no protocols exist yet to negotiate this trajectory with ATC.

Identified deficiencies

The nature of UAV missions is new compared to manned aviation. Mission types like border patrol, geographical surveys and search and rescue, require UAVs to fly missions that are not common to ATC. This is in contrast with manned aviation where point-to-point flights are most common. In fact, UAV missions are carefully planned, and might only be irregular for controllers. Furthermore, long endurance missions cannot always be planned in advance, resulting in trajectory updates. Trajectory information can provide predictability in irregular mission and sudden mission updates.

Opportunities

The opportunity is that trajectory information is already available on the ground in the UCS. Trajectory information makes the route explicit, and performance monitoring can be performed with early detection of deviations [22]. With trajectory information the extrapolations of aircrafts' positions for conflict prediction for ATC can be performed over a longer time-horizon and therefore more strategically. In addition, to eliminate uncertainties associated with prediction, trajectory updates can be exchanged directly. A UAV trajectory depiction can improve UAV predictability.

Enabling technologies

Controller Pilot Data Link Communication (CPDLC) applications enable the exchange of clearances and messages between controllers and pilots. In commercial aviation, datalinks have been in use for a considerable time. The Aircraft Communications Addressing and Reporting System (ACAS) facilitates data exchange between aircraft and airline operations centers. The Eurocontrol CPDLC program at the Maastricht Upper Area Control Center recently introduced datalink communication via Future Air Navigation Systems (FANS) and the Aeronautical Telecommunications Network (ATN) [23]. Air traffic demand is anticipated to grow substantially in the coming decades. Yet, controllers have a limited number of aircraft they are able to handle simultaneously. Until recently, the strategy to gain capacity is to subdivide airspace sectors. However, that strategy has reached the point of diminishing returns in high-density traffic regions. New automated separation assurance functions are expected to overcome the foreseen limitations. The two primary separation assurance concepts are ground-based automated separation assurance and airborne self-separation. The former technology is developed by Erzberger for NASA [24]. The latter technology, self-separation, is considered to be a final phase of TBO. The focus in this study is on near-term, therefore self-separation is not relevant yet.

Erzberger's Advanced Airspace Concept (AAC) lets the automation monitor and manage nominal trajectory-based operations of equipped aircraft, while the operator handles offnominal operations. In this system the ground automation is responsible to maintain separation between aircraft. It is responsible to detect strategic medium-term conflicts (typically up to 20 minutes), but it is also responsible for detecting tactical short-term conflicts (typically up to 3 minutes). The strategic system is hosted on the Automated Trajectory Server and is continuously analyzing flown trajectories and generating new conflict-free trajectories. A separation-assurance system, which activates in the event of a failure in the primary ground-based system, is another essential element of the AAC. This system is called Tactical Separation Assured Flight Environment.

Pilots of appropriately equipped aircraft operating in airspace under control of this new system will have an increased freedom to downlink trajectory change requests to the ground system. Aircraft in the sector will be able to request and receive trajectory changes concurrently. The ground-based system ensures that all uplinked trajectories will be mutually free of conflicts. The details of a trajectory negotiation process are being developed jointly by the Radio Technical Commission for Aeronautics (RTCA) SC-214 and the European Organisation for Civil Aviation Equipment (EUROCAE) WG78, including 4D Trajectory Datalink Services (4DTRAD) [25]. The essence of this negotiation process is captured by three types of datalink services: trajectory monitoring, trajectory clearance uplink and clearance request downlink [26]. Aside from trajectories, radio frequency changes, cruise altitudes, climb, cruise and descent speeds are communicated over datalink. The proposed AAC architecture is visualized in Figure 2-1.

RTCA SC-214/EUROCAE WG-78 Work Package 2 develops the new standards for 4DTRAD. According to plan, this standard should have come available in December 2011. In the end, this work results in an extension for the CPDLC set, an integration of new navigation and communication devices, and the option of trajectory negotiation. At the moment, the committee/work group is still dealing with interoperability issues between ATN and FANS.



Figure 2-1: The Advanced Airspace Concept system architecture, which enables the exchange of clearances and messages between controllers and pilots [24].

In the near-term there is no enabler to facilitate trajectory negotiation. For the reason that 4DTRAD standards are almost ready, designing a customized trajectory negotiation solution is not profitable. Therefore, trajectory information is initially not considered for implementation.

2-3 Conflict prediction

Many Cockpit Display of Traffic Information (CDTI) and Airborne Separation Assurance Systems (ASAS) display concepts exist that include conflict prediction algorithms which predict future loss of separation in case the current state or plan is maintained [27]. Yet, no commercially available concept informs the operator of the effects of changes to the current state, although it is essential for an operator to know how a maneuver impacts future separation to obtain level 3 situation awareness. It is found that in nautical navigation displays the underlying concept of providing information on the effects of changes to the current track was successfully implemented 40 years ago, but not extensively used ever since [28].

Tadema et al. [29] defined conflict probing for aviation as predicting the future separation between ownship and hazards for a set of ownship velocity vectors - representing possible combinations of track, flight path angle (FPA) and speed - up to a predefined horizon or lookahead time. Separation requirements result in a cylindrical volume. Predefined separation criteria, e.g. thresholds to define loss of separation and a collision hazard, help to distinguish future conflicts from loss of separations and from collision hazards, all with their corresponding time-to-conflict. Conflict probing supports level 3 situation awareness and aids the operator in determining, selecting and assessing maneuvers. Results from an initial evaluation show conflict probing provides an improvement in the assessment of the traffic situation, resulting in more effective and efficient conflict resolution maneuvers, and less unwarranted maneuvers [11].

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To illustrate the concept of probing, an example from Tadema is given. Figure 2-2 shows a top view of an example conflict geometry resulting from the presence of converging traffic. Vehicle A represents ownship, vehicle B is the intruder aircraft; the dashed lines represent the current tracks. Initial bearing of the intruder is 290, initial range is 5 NM. The intruder's track is 050, flying level at a speed of 250 kts. Both airplanes are at the same flight level. The depicted conflict track band and conflict probe result from probing for a range of variations of the ownship track angle for the current FPA and speed. The separation criteria (yellow) used in this example are 1 NM lateral and 1 kft vertical. The collision hazard criteria (red) used in this example are 0.25 NM lateral and 500 ft vertical. Note that although the separation requirements result in a cylindrical volume around the intruder, and the top view would yield a circle, the probing area shown in Figure 2-2 does not represent this circle. The contours of the yellow area indicate the instants at which the separation circle is penetrated, and the red area at which the collision hazard circle is penetrated, in case ownship changes its track in that particular direction.



Figure 2-2: Top view of an example conflict geometry with conflict probing applied, where vehicle A is the UAV and vehicle B an intruder.

The potential benefit of conflict probing is the shift of focus from detection to prediction. Previously, displays were optimized for traffic depiction, so the pilot can detect traffic as fast as possible. This focus on detection compared to prediction has disadvantages. First of all, traffic supply has changed drastically, what makes it harder to achieve a sufficient level of future conflict awareness without support for the prediction task. Secondly, pilots are generally not being trained to extrapolate traffic based on absolute position data, as controllers are [30]. It is concluded that the way the data is presented to a pilot has significant impact on the mental effort needed for prediction [31]. Furthermore, the capability of a pilot to mentally extrapolate traffic depends on the conflict geometry. Geometries with changing altitudes or different velocities make mental prediction very hard. Thirdly, computers have become so powerful that support is realizable. A difference between pilots and controllers is that controllers tend to separate more conservative than pilots, because their responsibility is the separation of all aircraft. In general it is concluded that conflict prediction is hard for human beings.

Particularly, in an experimental stage, UAVs demand additional controller effort. UAV mission types like geographical surveys or border patrol require their theater of operation to be dependent on specific ground surfaces. This way, UAVs operate anywhere in airspace, also close to air routes. Furthermore, UAV flight dynamics are initially uncommon to controllers, and predictions will be made on the safe side. A controller should, however, be able to perform the aforementioned tasks in his airspace sector efficiently without restricting other traffic so much that aircraft will be delayed. Conflict probing seems, from an initial evaluation on a CDTI, a concept that can also be useful in assisting the controller with the early detection of future conflicts, and providing information about possible prevention maneuvers, relieving controller from the prediction task.

2-4 Concluding remarks

In this chapter, an explanation of separation margins is given. Next, opportunities in sharing information between UCS and ATC are identified. Opportunities exist in the exchange of state information and the transmission of trajectory information to ATC, but no enablers exist for a near-term implementation. Conflict probing might assist in maintaining separation in an experimental stage. The next chapter addresses the differences of conflict probing in an ATC environment, and defines requirements for a design and implementation.

Near-term opportunities in technology

Chapter 3

Requirements for ATC support

After Chapter 2 identified the opportunities of conflict probing as support tool for the early detection and prevention of conflicts situations between UAV and other aircraft, this chapter analyses four relevant questions that differentiate the ND application from the ATC application. The analysis and trade-offs lead to requirements for the design and implementation. The four relevant questions are:

- Are changes to the conflict prediction algorithm necessary?
- Are the required parameters for the conflict prediction algorithm observable in radar surveillance data?
- What different constraints apply to the ATC display concept?
- What is the data quality, and what is the impact of it?

3-1 Conflict prediction algorithm

In this section it is analyzed whether the conflict probing algorithm needs adjustments before it can be applied to an ATC environment. In the UCS application of conflict probing, the UAV is always aircraft A, while Aircraft B is any intruder. This situation does initially not change, because conflict probing for ATC is designed specifically for UAV support in nonsegregated airspace. Therefore, the algorithm still complies. Also, the computational load is in the same range as for the conventional concept. Although the computational load is well within the realm of current generating computer architectures, the conflict probing algorithm demands a considerable computational load [16]. It should be noted that this demanded load may never impact the operational environment:

Requirement: The computational load of the conflict probing should not impact the operational environment.

3-2 State observability

State observability in the context of conflict probing is whether all relevant parameters for conflict probing can be extracted from the ATC surveillance sensors. To find out which parameters are needed, a more fundamental understanding of the conflict probing algorithm is needed. For this purpose, the first order equation for the separation S between two aircraft A and B is given in Equation 3-1, which can be expanded in components, see Equation 3-2. Equation 3-3 contains all relevant parameters [16]. Here, x_{A0} , y_{A0} , z_{A0} and x_{B0} , y_{B0} , z_{B0} are the initial positions of UAV and intruder; v_A , v_B velocities; Φ_A , Φ_B track angles;, γ_A , γ_B flight path angles, and time t.

$$S = \left| \overrightarrow{AB} \right| \tag{3-1}$$

$$S = \begin{vmatrix} x_B(t) - x_A(t) \\ y_B(t) - y_A(t) \\ z_B(t) - z_A(t) \end{vmatrix}$$
(3-2)

$$S = \begin{bmatrix} x_{B0} - x_{A0} + (v_B \cos \gamma_B \sin \Phi_B - v_A \cos \gamma_A \sin \Phi_A)t \\ y_{B0} - y_{A0} + (v_B \cos \gamma_B \cos \Phi_B - v_A \cos \gamma_A \cos \Phi_A)t \\ z_{B0} - z_{A0} + (v_B \sin \gamma_B - v_A \sin \gamma_A)t \end{bmatrix}$$
(3-3)

The algorithm determines the separation for the current positions, with the current velocity for a range of tracks. For ATC, variations in velocity are not considered. The effect of separation is studied over time until the look-ahead time is reached. The probe elements for different tracks where separation is below the threshold are colored. This results in the conflict zones as they are already known. Based on Equation 3-3, the minimum set of aircraft parameters required are:

- Current lateral and longitudinal position of UAV and intruder
- Current altitude of UAV and intruder
- Current velocity of UAV and intruder
- Current track of UAV and intruder
- Current flight path angle of UAV and intruder

The listed parameters define another requirement for the design and implementation:

Requirement: A real-time feed of aircraft position, velocity, altitude, track and flight path angle should be available.

3-3 ATC display concept

The target display - the PPI - has a fundamentally different setup. This different setup is analyzed. Some differences lead to additional requirements for the design and implementation. The encountered differences are subdivided into three categories: **Reference** The reference of the display changes from ownship-referenced to sitereferenced. Originally, on a PPI, the reference is the ATC site. Today this is not stringent anymore; the radar site is not always coupled with the ATC site and computerization enabled practically any controller-preferred reference.

Orientation The orientation changes from ownship-oriented to north-oriented. A PPI needs to cover the complete airspace sector at all times. In general, every aircraft is of equal importance. For this reason, a fixed orientation to the magnetic North is chosen, a common orientation for maps.

Size and range The range of a surveillance radars is larger than the range TCAS II, the latter is limited to 40 NM [7]. Moreover, the size of the PPI is much larger than a ND. Furthermore, on a ND, only traffic flying at altitude levels of +3500 ft and -3500 ft from ownship is displayed by default. The main reason is that other traffic is not of interest, and may cause cluttering. For ATC all altitudes in a an airspace sector are relevant, since responsibility for traffic deconfliction is officially delegated to ATC.

The change in reference and orientation make UAV position less trivial than before. However, a controller knows where his assigned aircraft are located anytime. Moreover, a controller knows that conflict probing belongs to the UAV. In turn, with a significant increase in range, a map projection should be considered, a method of representing the surface of a sphere or other three-dimensional body on a plane. Map projections are necessary to create maps of three-dimensional bodies. All map projections distort the surface in some fashion. Depending on the purpose of the map, different map projections exist in order to preserve some properties of the body, usually at the expense of other properties. The requirements for the display concept are:

Requirement: The conflict zones should be conformally displayable on a PPI.

Requirement: The ATC display concept should comply with the map projection of the ATC/C2 target system.

3-4 Data quality

After section 2-1 explained surveillance sensor accuracies in general, the impact of sensor accuracies on conflict probing is studied next. Conflict probing is the computation of future separation with other traffic, both for current velocity vector and variations to this. In the computation, position and velocity accuracies are taken into account. The result of the computations is presented as ownship referenced areas or volumes where the separation will be below threshold. These areas or volumes, called conflict zones, also account for prediction accuracies. Data quality should be sufficient to limit the false alarm (FA) rate.

The next paragraph introduces the general trade-off between tactical ATC and prediction accuracy. Then, a reference case is described for ADS-B from previous research. Finally, the requirements for radar sensor accuracies are described qualitatively.

3-4-1 Look-ahead time

The look-ahead time is always a trade-off between the tactical level of ATC and prediction accuracy. Tactical ATC usually takes place between 60 and 180 seconds before conflict. At smaller time-to-conflicts, at approximately 50 seconds before conflict, a TCAS Traffic Advisory is given [32]. At larger time-to-conflicts, maneuvering is called strategic. The prediction accuracy is in the current concept based on the worst-case performance of the surveillance sensor, and equals the accumulated effect of position accuracy and velocity accuracy over the look-ahead time.

The look-ahead time provides a fixed time-horizon for conflict predictions, and simultaneously bounds future position accuracies. The reason behind a balanced look-ahead time is the desire to keep the FA rate as low as possible. So, a decreased velocity accuracy demands a reduction in look-ahead time to prevent an increase in FA rate. An FA, however, would only occur if ATC actually intervenes based on the information. If ATC would be aware of the deteriorated accuracy, it may wait until the accuracy is at an acceptable level. A balanced look-ahead time does not improve accuracy, but it at least provides a realistic conflict assessment.

Requirement The look-ahead time of conflict probing for ATC should be used to limit the FA rate.

3-4-2 Conflict probing and ADS-B

In the Minimum Operational Performance Requirements for ADS-B, a minimum horizontal position accuracy for ADS-B is set to Navigation Accuracy Categories for Position (NACp) level 5, which corresponds with 0.5 NM (95%)[33]. For Navigation Accuracy Categories for Velocity (NACv), the requirements are up to the manufacturer. All NACp and NACv levels are listed in Table 3-1. ADS-B requirements for ATC purposes are more stringent defined by the FAA. In ADS-B Out Performance Requirements To Support ATC: Final rule, NACp category 8 (<92.6 m) is required for horizontal/vertical position accuracies (95%)[34]. Initially, the determination of NACv was up to the manufacturer; for ATC, NACv category 1 is mandated (<10 m/s) (95%).

Tadema states that these current ADS-B Out performance requirements are still inadequate for conflict probing [13]. It was illustrated with examples that with higher NACv categories, a considerable reduction of conflict space was realized, thus a reduction in FA rate. NACv categories 2 and 3 would deliver a consistent performance instead. On-line state estimators provide aid to reduce the estimation errors below the ATC's final rule level.

3-4-3 Actual track accuracies

The actual performance of radar surveillance sensors is studied, and specific differences between UAV surveillance data and ATC surveillance data are addressed. The relevant differences lead to requirements for the design and implementation.

Current en-route ATC radars have a 2.4 NM (99%) required measured separation accuracy [17]. For this requirement, an aircraft flying at 600 kts at a range of 200 NM is chosen. This accuracy is rather low, what means that these radar sources cannot be used without a radar tracker.

NACp	Accuracy bound	NACv	Accuracy bound
0	>= 10 NM	0	>=10 m/s
1	$< 10 \ {\rm NM}$	1	$< 10 { m m/s}$
2	< 4 NM	2	$< 3 \mathrm{m/s}$
3	$< 2 \ \mathrm{NM}$	3	<1 m/s
4	$< 1 \ \mathrm{NM}$	4	< 0.3 m/s
5	$< 0.5 \ \mathrm{NM}$		
6	$< 0.3 \ \mathrm{NM}$		
7	$< 0.1 \ \mathrm{NM}$		
8	$< 0.05 \ \mathrm{NM}$		
9	$< 30 {\rm m}$		
10	$< 10 {\rm m}$		
11	$< 3 \mathrm{m}$		

Table 3-1: Navigation Accuracies for Position (NACp) and Velocity (NACv)(95%)[33].

Radar trackers improve the measured state information with state-estimators. The actual performance of a radar tracker depends on many parameters, e.g. number of sensors, used algorithms, available computational power. It is hard to specify radar tracker performance in general, while the performance is essential for the profits of conflict probing. Therefore, the performance of the target radar surveillance tracker is analyzed in Chapter 4.

A major difference of radar trackers is the availability of actual estimated accuracy levels. In the conventional conflict probing concept, the theoretical conflict area is integrated with the future position accuracy area. In ADS-B, the accuracy level for track is not provided in the message structure; it has to be obtained from the worst-case combinations of the velocity performance level. When using a fixed value for position and velocity accuracy, a conservative worst-case accuracy has to be used. With a dynamic accuracy, for those situations exceeding the worst-case assumption, the FA can be reduced, together with the size of the conflict zone. In the ATC application, actual sensor performance should be involved to give a more realistic conflict assessment. Also, actual sensor performance should be used to limit clutter.

Requirement: The conflict zone accuracy should be based on actual track accuracies.

Requirement: The actual surveillance sensor performance should be applied to limit the FA rate.

Another difference in an ATC environment concerns the changed reference. If conflict probing is not applied from ownship as reference, accuracies of both ownship and intruder should be taken into account. In fact, UAV position is also uncertain for ATC, just like intruder position. In that case, uncertainties double, which affects the FA rate considerably. This can be resolved by applying conflict probes from ownship's GNSS state information, that is currently only available from the UCS. As soon as GNSS state information is available from the radar tracker, this can also be used. **Requirement:** The UAV state information used by the conflict probing algorithm should originate from GNSS state information.

3-5 Concluding remarks

The requirements defined in this chapter are subdivided into three categories to structure the design and implementation. The three categories are connectivity, data integration and data presentation. A list of categorized requirements can be found in Table 3-2.

Chapter 4 continues with the radar surveillance data analysis, as required from Subsection 3-4-3. The impact of radar surveillance data quality leads to an enhanced concept, based on requirements on data integration (4),(5) and (6). After that, Chapter 5 follows with the design and implementation of the concept into the MASE, based on requirements (1) and (2) on connectivity, requirement (3) on data integration, and requirement (7) and (8) on data presentation.
Table 3-2: The categorized requirements for level 3 UAV situation awareness support for ATC.

Category	Requirement
Connectivity	 (1) A real-time feed of aircraft position, altitude, velocity, track and flight path angle should be available. (2) The UAV state information used by the conflict probing algorithm originates from GNSS state information.
Data integration	 (3) The computational load of the conflict probing should not impact the operational environment. (4) The look-ahead time of conflict probing for ATC should be used to limit the FA rate. (5) The conflict zone accuracy should be based on actual track accuracies. (6) The actual surveillance sensor performance should be applied to limit the FA rate.
Data presentation	(7) The conflict zones should be conformally displayable on a PPI.(8) The ATC display concept should comply with the map projection of the ATC/C2 target system.

Chapter 4

Conflict probing for ATC

This chapter describes the analysis of surveillance data quality. The data quality should be sufficient to limit the FA rate. The results of this feasibility analysis are compared with previous studies on surveillance sensor accuracies. Next, the impact of the actual data quality is studied, what results in enhancements to the conflict probing for ATC concept, based on requirements (4),(5) and (6).

4-1 Feasibility analysis

The actual performance of a radar tracker is studied from an export of an ATM Surveillance Tracker And Server (ARTAS) in the Netherlands. ARTAS is a tracker system that is used at over 30 European sites, both civilian and military. The server is designed to establish an accurate air situation picture of all traffic over a well-defined geographical area, and to distribute the relevant surveillance information to a community of user systems. The message format in which the data is transmitted or exported will be discussed in Subsection 5-1-2. In track updates in the ARTAS export, estimated accuracies for position, velocity and acceleration are contained. This data is analyzed extensively. Beforehand, the assumption is made that the estimated accuracies are correct. It is not possible to verify this estimation in limited time.

In total, over 2,620,000 track updates in a time period covering 24 hours are analyzed. Almost 2,140,000 track updates could be linked to a Mode 3/A transponder code. Normally, a track is updated every 4.8 seconds, closely related to the radar sweep time. It is assumed here that a track is stable when it has more than 10 track updates. Besides, it is assumed that an aircraft will be airborne, or has been in air, to filter for ground traffic. After filtering for at least 10 track updates remained, belonging to about 7,200 tracks. All track updates contain estimated accuracies for position and velocity, expressed as standard deviations in Cartesian coordinates. For a future implementation, the Cartesian coordinates can be used individually. For the study, the Cartesian components are combined into a single value, the vector length, though this is a worst-case approach. The mean estimated accuracy of all track updates for a single track is from now on called the mean track accuracy, expressed in a 95% confidence interval. The mean of a set of mean track accuracies is from now on called the general track

accuracy (95%).

To get a better understanding of the factors impacting the general track accuracies, three hypotheses are defined:

- the mean track accuracy strongly depends on the number of track updates;
- the mean track accuracies differs with time of the day;
- an individual track accuracy improves with the number of track updates.

The hypotheses are verified with an analysis of the ARTAS export, starting with the first hypothesis.

4-1-1 Accuracy depends on number of track updates

Intuitively, the mean track accuracy can depend on the number of track updates; as more measurements are present, the mathematical algorithm for track smoothing can perform better state estimations. It is of main interest to study the effect of different minimum numbers of track updates on the general track accuracy. Simultaneously, the distribution of tracks and track updates over the minimum number of updates is studied. The results are listed in Table 4-1. Note that each track update generally takes 4.8 seconds. The position and velocity accuracy are general track accuracies in meters. The standard deviations are general track accuracy standard deviations in meters. From the data it is concluded that accuracies improve and stabilize with the number of track updates. The position accuracy improves two times from 10 track updates to 150. The standard deviations improves 5 times, with the same gain achieved from the increase of the track updates minimum from 10 to 20, as from 20 to 150. The velocity accuracy also shows improvement. The initial improvement from 10 to 20 minimum track updates is not comparable with the improvement in position accuracy; the velocity accuracy is soon quite accurate. In the remainder of the research, the assumption is made that a representative track contains 95% of all track updates. Such a track has on average at least 60 track updates. The coupled general position accuracy is 127.38 meter, with a standard deviation of 112.64 meter. The associated general velocity accuracy is 12.93 meter with a standard deviation of 7.60 meter.

4-1-2 Accuracy differs with time of the day

Daily ATC routines consist of different phases, with significantly changing aircraft supply and weather conditions. For example, Amsterdam Airport Schiphol serves as a West European hub; a lot of traffic arrives at approximately the same time, and after a short while departs all at once. Likewise, daytime and nighttime operations are distinguished; in aircraft supply, as well as in assigned air routes. Increased aircraft supply, increases the number of radar echoes, as well as the ARTAS computational load. Furthermore, different air routes have different radar coverage. Also the nature of tracks differ, when in busy airspace a holding is engaged, multiple aircraft are continously maneuvering close together. Finally, looking at the weather, precipitation and temperature impact radar propagation. All circumstances impact sensor accuracy, therefore it is expected that accuracy differs with time of the day.

An overview of the results on an hourly basis is illustrated in Table 4-2. The crowded early morning skies (6-11 hour) show a higher accuracy, than the less busy hours right after (11-15

			Position	accuracy	Velocity	accuracy
Min. updates	Tracks %	Track updates $\%$	Mean	Stdev	Mean	Stdev
10	81.33	97.93	186.72	366.79	16.38	11.32
20	77.92	97.71	163.73	184.42	15.48	10.07
30	75.63	97.47	154.92	145.71	14.97	9.52
40	72.64	97.03	145.68	135.88	14.28	8.80
50	68.95	96.33	136.06	128.95	13.51	8.19
60	65.82	95.61	127.38	112.64	12.93	7.60
70	63.51	94.98	120.47	104.34	12.49	7.15
80	62.07	94.53	116.22	99.16	12.21	6.88
90	60.46	93.96	112.26	95.97	11.96	6.64
100	59.37	93.52	109.52	93.20	11.81	6.51
110	58.19	93.00	107.47	91.88	11.65	6.40
120	56.96	92.42	105.53	89.18	11.51	6.30
130	55.97	91.90	103.66	86.82	11.35	6.15
140	55.04	91.37	101.47	82.34	11.20	5.99
150	53.87	90.66	99.06	79.58	11.02	5.82

Table 4-1: General position and velocity accuracies for different minimum number of track updates.

hour). This effect has clearly nothing to do with aircraft supply, which is less. This effect is probably due to deteriorated weather conditions, which become worst between 14 and 15 o'clock. On an hourly basis, the mean position accuracy (95%) in the worst hour degrades to NACp category 6. It almost reaches NACp category 8 in the best hour. For the mean velocity accuracy, in bad hours it degrades to 30 m/s, i.e. NACv category 0, while at best, approximately 15 m/s is reached, i.e. 1.5 times NACv category 1.

4-1-3 Development of individual track accuracies

To comprehend and make predictions about the development of track accuracies with time, a closer look is taken at individual tracks. Subsection 4-1-1 already illustrated the relationship between number of track updates and mean track accuracy. To analyze individual tracks, in Figure 4-1 and 4-2 track position and velocity accuracies are plotted for every track update of each track. The tracks shown are 10 subsequent tracks in the time span between 21 and 22 hour, with a required minimum of 60 track updates. From that perspective, only 60 track updates are plotted. The step size is 5 track updates, because a smaller step size would cause a ripple effect, which distracts from the results.

It can be concluded that for small track updates, every new update means an improved estimation. Somewhere between track update 25 and 45, all tracks deteriorate. The tracks were all initialized between 21 and 22 hour, what suggests aircraft can be impacted by the same external influence, which can be technical or meteorological of nature. The RNLAF confirms technical and meteorological influences are indeed the main contributors to varying accuracies.

In short, the figure shows that estimated track accuracies generally improve with time, but can deteriorate occasionally. Furthermore, deteriorations commonly impact multiple tracks.

			Position	accuracy	Velocity	accuracy
Hour	Tracks	Track updates	Mean	Stdev	Mean	Stdev
0	61	36121	148.88	152.53	12.94	9.11
1	19	6824	134.70	134.96	13.05	9.01
2	13	5707	108.43	98.00	10.08	6.63
3	47	22311	94.00	67.84	10.45	5.34
4	54	21845	74.83	52.36	8.56	3.00
5	165	57657	82.20	51.39	10.08	4.31
6	299	103492	88.49	64.11	10.39	4.85
7	308	119028	97.42	69.13	10.43	4.82
8	336	121039	102.50	71.64	11.38	5.50
9	482	172576	117.32	102.42	12.44	6.93
10	541	189190	154.18	134.11	14.66	8.38
11	542	188137	152.07	122.20	15.09	8.31
12	477	162920	155.91	133.14	15.02	8.21
13	511	166744	160.93	119.98	15.95	8.66
14	484	145224	184.88	163.56	17.03	9.32
15	328	105822	125.17	99.31	12.76	7.67
16	217	73114	100.93	80.29	10.88	6.25
17	250	90811	104.26	88.74	11.40	6.78
18	182	64904	93.83	59.30	10.05	4.65
19	163	54737	89.08	67.36	9.65	4.79
20	180	61485	81.56	58.25	9.09	4.07
21	118	43786	72.63	40.29	8.20	3.76
22	63	23942	87.30	73.99	8.55	4.50
23	21	5868	131.71	119.76	11.58	8.11

Table 4-2: General position and velocity accuracies for different hours of the day.



Figure 4-1: Development of estimated position accuracy of individual tracks with track updates.

To conclude on the radar tracker accuracies, the worst general position accuracy is about five times NACp category 8, required for ATC on ADS-B. The best general position accuracy approximates NACp category 8. The worst general velocity accuracy deteriorates to three times NACv category 1. The best general velocity accuracy is about 1.5 times NACv category 1. Although the estimated radar tracker accuracies are much better than the radar sensor accuracies, NACv category 1 or higher seems unfeasible for ARTAS. Noticeably, the standard deviation in the general track accuracy is significant.

When using a fixed value for position and velocity accuracy in conflict probing, a conservative worst-case accuracy has to be used. With a dynamic accuracy, for those situations exceeding the worst-case assumption, the FA is reduced. For instance, a conflict situation with a worst-case accuracy leads to a larger conflict zone than with actual accuracy. When the conflict zone with worst-case accuracy is predicted on the current track, while the conflict zone with actual accuracy is not, this prediction is called a false alarm.

In the next section, actual prediction accuracies are specified. Then, the potential effects of dynamic accuracies are further analyzed and result in a design in Section 4-3.

4-2 Actual prediction accuracies

The contribution of track accuracies over the prediction time is now studied for different sensor types. Table 4-3 gives an overview for different time-to-conflicts, expressed in meters. The first row considers conflict probing from ATC-only perspective, the others are applied based on UCS state information, which doubles accuracy. The enhanced ADS-B row is ADS-B with on-line state estimations. The tracker accuracies, in turn, are extracted from the previous analysis. Tracker represents general track accuracies. Tracker best and worst hour are the



Figure 4-2: Development of estimated velocity accuracy of individual tracks with track updates.

Table 4	1-3:	Future	position	accurac	y in	meters	and	percentage	of tl	ne AN	ISD,	after	position	and
velocity	ассі	uracy e	xtrapolat	ions for	diffe	erent su	rveill	ance senors	s (959	6)				

	Initial	$10 \mathrm{~s}$	$60 \mathrm{\ s}$	%ANSD	$120~{\rm s}$	%ANSD	$180~{\rm s}$	%ANSD
ATC with ADS-B	200	400	1400	15%	2600	28%	3800	41%
UCS with ADS-B	100	200	700	8%	1300	14%	1900	21%
Enhanced ADS-B	110	110	160	2%	220	2%	280	3%
Tracker	250	450	1450	16%	2650	29%	3850	42%
Tracker best hr	150	250	750	8%	1350	15%	1950	21%
Tracker worst hr	500	700	1700	18%	2900	31%	4100	44%

general track accuracies in the hours with the relatively best and worst general position and general velocity accuracy. It is observed that at a prediction time of 60 seconds, all mean position inaccuracies stay within about 1 NM (1852 meter). At 120 seconds, they are all within 1.5 NM (2778 meter). At 180 seconds, the worst hour position accuracy drops below 2 NM (3704 meter), the best hour remains within 1 NM (1852 meter). In the next section, the actual prediction accuracies are used as a reference to define enhancements to the conflict probing concept and specify data quality requirements.

4-3 Dynamic conflict zone accuracies

From the conclusion of the feasibility study, there is a need for additional analysis into actual estimated accuracies to replace worst-case accuracies. The worst-case accuracies lead to a dramatic increase in conflict size, compared to the initial concept. The actual estimated



Figure 4-3: Conventional separation margins and dynamic separation margins compared.

accuracies have a considerable standard deviation; accuracies will vary from poor to moderate, referring to the tracker's best and worst hour, and other accuracies in Table 4-3. To secure the FA rate and avoid cluttering at the same time, the theory of prediction accuracies and separation margins is combined into a new concept. After that, the controller is provided support to avoid false alarms. Also, support is provided to avoid missed detections. The section is concluded with an example scenario.

4-3-1 Dynamic separation margins

In Section 2-1, the current ANSD is concluded to be rather conservative, especially when actual estimated accuracies are available instead of worst-case accuracies. To optimize the separation margins, the separation margin for sensor inaccuracies, as contained by the ANSD, can also be dynamically assigned. The separation margin then becomes the accumulated effect of the temporal and spacial margin, and the future position accuracy. In case of relatively good track accuracies, the separation margin is significantly less than the current ANSD. In case the separation margin is more than the ANSD, the gain is the part of the future position accuracy that is now part of the ANSD. The result here is that sensor inaccuracies do not contribute twice to the computation of the conflict zone anymore. Figure 4-3a and Figure 4-3b show this different approach. The gray area T/S represents the default temporal and spacial margin. SI stands for sensor inaccuracies, which is replaced by AESI: actual estimated sensor inaccuracies. The black outer circle in Figure 4-3b is the ANSD as a reference. The dynamic conflict zone is here smaller than the ANSD. It can, in turn, also be larger.

Dynamic separation margins are supported with valid arguments, but the generally tight regulations on separation margins for ATC cause legal issues today. When the ANSD is enforced by law, and UAVs are separated at 5 NM, UAVs may in no circumstance violate this margin. In the computation of a conflict zone, it is considered that at least 2 NM of the ANSD originate from sensor inaccuracies. These sensor inaccuracies margins are now dynamically assigned. In fact, with dynamic separation margins the final separation is at least 3 NM, but not always more than 5 NM. Hence, dynamic separation margins do not always comply with

current law. Nevertheless, the ANSD must be met in the end, not particularly from the first prediction.

From the general prediction accuracies theory in Subsection 2-1-3, future position accuracy primarily consists of velocity accuracy extrapolations. Consequently, it is expected that future position accuracy improves with a reduction of time-to-conflict. A controller can again optimally utilize the tactical ATC time window to monitor the prediction outcome. It is possible that ownship eventually complies to the ANSD, before conflict.

To numerically support the likeliness of compliance with the ANSD, a simple conflict situation is assumed where an aircraft approaches an intruder heads on with a velocity of 300 kts. At different time-to-conflict TTC in the tactical ATC window, the bearing is calculated to avoid the ideal conflict zone ICZ, and separately to avoid the actual conflict zone ACZ, including future position accuracies based the general track accuracy. Additionally, the radius of the respective conflict zone is given. The results are listed in Table 4-4. It is concluded that with actual estimated track accuracies, the bearing between the ideal and actual conflict zone constantly differs approximately 10 degrees. Furthermore, it is concluded that between a time-to-conflict of 180 seconds and 60 seconds, the tactical ATC window, the future position accuracy decreases with 1.75 NM.

Next, it is studied whether aircraft with headings between the ICZ heading and ACZ heading, actually benefit from this improved future position accuracy. It is taken into account that controllers assign tracks with a resolution of 5 degrees. Table 4-5 shows the lateral deviation for headings between 10 and 20 degrees, initiated at 180 seconds. It is clear that a heading of 20 degrees immediately turns ownship out of future conflict. It is also clear that a heading of 10 degrees result in a conflict. For other headings, a comparison between the columns in Table 4-4 and Table 4-5 is made to conclude whether a heading eventually becomes free of future conflict with time, expressed in the time-to-conflict. The third column in Table 4-5 shows that almost every heading becomes free of conflict eventually, whereof the four smallest headings after the tactical ATC level. Besides the maneuver time instant at 180 seconds, different maneuver time instants are studied. As long as the controller assigns headings with a resolution of 5 degrees, also a maneuver at 120 seconds ends up free of conflict. However, future position accuracy can also degrade occasionally, leading to a potential missed detection. From the data, potential missed detections are scarce, but should be monitored instead.

To conclude, the observability of actual sensor performance enables for dynamic separation margins. However, when the UAV separation margin is as low as the ANSD, it should be obeyed. It is illustrated that for radar tracker accuracies, in an ideal conflict situation, the ANSD can be respected when no accuracies are comprised in the conflict zones.

4-3-2 Accuracy limiting

When a future conflict has a severely degraded conflict zone accuracy at a tactical ATC level, it does not have to be depicted directly. Because a degraded conflict zone accuracy goes hand-in-hand with a high FA rate, it is better to wait for an improved accuracy. The theory of prediction accuracies tells that when the time to conflict reduces, the prediction accuracy improves - assumed that position and velocity accuracies are stable. Besides that, track accuracy naturally improves since a track generally becomes more stable with more track updates, and, hence, with time. This relationship is confirmed with the radar tracker study in Section 4-1-1. Tactical ATC is performed in the time span between 60 seconds and

TTC (s)	ICZ heading (deg)	ACZ heading (deg)	ACZ radius (NM)
180	9	19	5.29
170	10	20	5.15
160	11	21	5.01
150	11	21	4.86
140	12	22	4.72
130	13	23	4.57
120	14	24	4.43
110	15	25	4.28
100	17	26	4.14
90	18	28	3.99
80	21	30	3.85
70	23	32	3.70
60	27	35	3.56
50	31	39	3.41
40	37	44	3.27
30	45	51	3.12
20	56	61	2.98
10	72	74	2.84
0	90	90	2.69

Table 4-4: Ideal and actual headings to prevent future conflicts based on time-to-conflict and future position accuracy.

Table 4-5: Lateral deviation for headings between 10 and 20 degrees, initiated at 180 seconds, including the time-to-conflict where the aircraft becomes free of future conflict.

Heading (deg)	Lateral deviation (NM)	TTC (s)
10	2.64	-
11	2.92	10
12	3.19	30
13	3.46	50
14	3.74	70
15	4.02	90
16	4.30	110
17	4.59	130
18	4.87	150
19	5.16	170
20	5.46	>180



Figure 4-4: The dynamic conflict zone accuracies concept with a fixed sensor inaccuracies margin.

180 seconds to conflict, which usually allows the pilot enough time to consider several options. Herewith, the whole tactical ATC time window can be optimally used for conflict prevention. In the meantime, the controller should not be disturbed with large conflict zones, but the pending conflict situation should be indicated subtly instead. Only when conflict are based on accurate state information, they are depicted. Conflict zones should also be depicted when there is no time left in the tactical ATC window. The display threshold is quantified next.

To specify the display threshold, Table 4-3 is reviewed as a guideline. From this table, the first conclusion is again that the linear extrapolation of velocity accuracy is the main contributor to future position accuracy. Another conclusion that is drawn, is that worst-case future position accuracy at 180 seconds is 4100 meter (2.2 NM). At 120 seconds, the worst future position accuracy is 2900 meter (1.6 NM). In any case, even the worst hour general track can apply conflict probing somewhere between 120 and 180 seconds with a future position accuracy smaller than 2 NM. For the operational concept, it is feasible to make 2 NM the upper limit for conflict probing. Moreover, it is relevant to make 2 NM a fixed sensor accuracy margin. The rationale behind a fixed separation margin is predictability for controllers, moreover a situation they are used to. The system then monitors that the future position accuracy remains within 2 NM for responsible maneuvering. When the future position accuracy degrades to over 2 NM, the controller is advised to postpone maneuvering. Figure 4-4 shows the dynamic conflict zone accuracies with DCZA, where accuracies within the blue area are tolerated.

4-3-3 Missed detection

After a maneuver in the responsible maneuvering window, it is not yet clear whether the aircraft will remain out of future conflict, or will only stay out of the ideal location of the future conflict. In the conventional concept the future position accuracy is added on top of the ANSD, the ANSD circle was located somewhere in the future position inaccuracy circle *FPI*, as in Figure 4-5a. In the dynamic concept it is part of the ANSD, where the T/S circle is located somewhere in the DCZA circle, in worst-case colliding with the intruder position, as shown in Figure 4-5b. A small chance exists that the controller instructs a heading into the future position accuracy area, as indicated qualitatively in Subsection 4-3-1 and limited in Subsection 4-3-2. In that case it is again rationally expected that the aircraft will be free



Figure 4-5: Different contributions of sensor inaccuracies to the conflict zone computation, where sensor inaccuracies are either added on top or are embedded.

of future conflict with time. In the meantime, the conflict area can appear striped to indicate the aircraft is not definitely out of future conflict.

To conclude, the dynamic conflict zone enhanced with accuracy limiting and missed detection monitoring, but without future position accuracies included, meets data integration requirement (4),(5) and (6). Finally, an example scenario is provided.

4-3-4 Example scenario

To illustrate the concept an example conflict geometry is shown in Figure 4-6. Aircraft UAV is heading into a heads-on conflict with aircraft TRF, flying at the same altitude with approximately the same velocity. The view in Figure 4-6a is the conventional conflict probe depiction. In this view the UAV can responsibly maneuver without taking future position in-accuracy into account, because with the estimated improvement in future position inaccuracy, the conflict is cleared in time.

As the future position accuracy is degraded, the conflict border turns red, advising to await responding. This view can be seen in Figure 4-6b. The "postpone maneuvering advise" is only be given in case there is sufficient time left in the tactical ATC window. Otherwise, the conflict zone with actual estimated accuracies is depicted without the upper limits.

After a maneuver, it is not yet clear whether the aircraft remains out of future conflict. A substantial heading prevents the future conflict immediately and definitively. The first thing that occurs after a substantial prevention maneuver is the conflict zone turning inactive, illustrated with transparent yellow. A rather conservative heading will likely head the aircraft into the dynamic sensor inaccuracies margin. It is expected the future conflict is prevented naturally with time. It may, on the other hand, never lead to a missed detection. To avoid



Figure 4-6: Conflict zone accuracy monitoring tells the controller when its responsible to maneuver without taking future position inaccuracies into account in a conventional depiction, and to postpone maneuvering with a red border encircling the conflict zone.

missed detections an indication is presented. As the aircraft heads into the future position accuracy area, between the solid conflict area and the yellow outer circle in Figure 4-7a, the conflict area will appear striped. With the stripes, an intermediate role between yellow - indicating caution - and transparent yellow - indicating caution after maneuvering. An example depiction is given in Figure 4-7b. As the conflict area turns into transparent yellow, the aircraft is out of conflict definitively.

4-4 Concluding remarks

In this chapter the surveillance radar analysis showed that general track accuracies show large standard deviations. A concept called dynamic conflict zones is introduced where actual track accuracies are monitored in the conflict probing concept. When the future position accuracy exceeds 2 NM, the controller is advised to postpone maneuvering. For future position accuracies smaller than 2 NM, no accuracies are comprised, since it is expected the future position accuracy naturally improves. Additionally, the concept provides an indication for pending conflict situations, to avoid missed detections. The presented concept meets requirements (4),(5) and (6). Although the design is proposed, the dynamic conflict zone accuracies are not yet comprised in the initial conflict probing for ATC implementation. The next chapter continues with the design and implementation of the concept into the MASE based on a real-time radar surveillance feed.



(a) Future position inaccuracy circle

(b) Future conflict most likely prevented

Figure 4-7: Example scenario of dynamic conflict zone accuracies, where a maneuver into the future position accuracy area is illustrated, where the conflict situation is most likely prevented.

Chapter 5

Design and implementation

In this chapter the design and implementation of conflict probing on the MASE is described, with a radar tracker feed of ARTAS. The target system is the Multi-Aegis Site Emulator (MASE) at the Air Operations Control Station (AOCS) in Nieuw Milligen, the Netherlands. The MASE is used by many NATO nations for Air Defense. Both military and civilian radars can be connected using many protocols. The advantage of MASE is that it has both C2 and ATC capabilities [10]. However, the MASE is a legacy system where modifications are hardly supported.

First, connectivity with the MASE is designed where the selected message format should comply to connectivity requirement (1). Then, the data integration platform is designed based on data integration requirement (4), after which data presentation on the PPI is developed according to data presentation requirements (7) and (8). The chapters ends with a schematic system overview.

5-1 Connectivity with the MASE

In this section the surveillance data protocols connected to the MASE are compared. This comparison leads to the design of the most feasible surveillance data protocol based on the connectivity requirements. The MASE is a complex system that has evolved over time. Its successor, the NATO Air Command and Control System (ACCS) was already mentioned in the 1980's, but is still not released. The MASE has several sensor inputs, but has no external input or output for experimental work. In current operations, a separate server hosts the Interactive Simulation Package (ISP), that adds a modern simulation system for air exercises into the MASE, on which simulations are performed [35]. The functionality is added by a wrapper that converts a simulation protocol into a radar protocol.

The functionality of ISP includes scenario preparation and execution, as well as online, real-time scenario modification. Normally, ISP is used in single site mode. However, by using the Distributed Interactive Simulation (DIS) protocol, a multi-site mode is enabled for exercises over multiple C2 sites. The DIS protocol is an IEEE standard for real-time platform level war gaming [36]. There is also a NATO standardization agreement (STANAG 4482, Standardized Information Technology Protocols for DIS, adopted in 1995) on DIS for modeling and simulation interoperability.

In the past, DUT implemented DIS into the DUT research simulator, basically simulating a multi-site mode exercise [10]. Traffic was simulated by the ISP and displayed on the DUT research UCS and on the MASE. The UAV originated and was controlled in the DUT research simulator, but was displayed on the MASE as well. UAV trajectories were drawn on the MASE beforehand, and could not be modified on-line. Additionally, the MASE seems not feasible for any other advanced technologies due to the limited support by the NATO Programming Center, partly because the system is being phased out. Besides that, it turned out that no real air picture can be combined with ISP, either live or recorded.

In the next subsection the available surveillance data protocols are compared. Based on the requirements for connectivity, this leads to the implementation of a specific surveillance data protocol.



Figure 5-1: Interconnections of the MASE with common surveillance protocols and tactical datalinks.

5-1-1 Available surveillance data protocols

To select the surveillance data protocol that is most feasible according to the connectivity requirements, the available surveillance data protocols are compared with each other. To get a better understanding of the interconnections of the complete ATC/C2 system, an overview is given first in Figure 5-1. In Figure 5-1 RSRP stands for Radar Southern Region and Portugal and is basically a radar protocol, containing individual radar plots. ICC stands for Integrated Command and Control Software for Air Operations and is a data buffer for modern military tactical datalinks. From this Figure, it becomes clear that only DIS scenarios can be loaded on the DUT research UCS. Despite DIS2RSRP, no RSRP2DIS is available. For state information, two approaches can be taken. Firstly, the RSRP and ASTERIX protocols can be studied. Secondly, a military tactical datalink, Link16, can be studied. RSRP is a very specific radar protocol providing the MASE with raw radar plots. ASTERIX is a well-standardized protocol, designed by Eurocontrol, that is used in civil and military radar trackers. Link 16, in turn, contains much information, including tactical and weapon information, but has security classifications applied upon it that make it hard to obtain.

From the list of requirements, a real-time feed of aircraft position, altitude, velocity, track and flight path angle is required, as well as actual estimated accuracies, that can only be provided by a radar tracker protocol. ASTERIX and Link 16 can provide this feed. From these protocols, ASTERIX is chosen, since it is highly-standardized and available without restrictions.

5-1-2 ASTERIX Category 062: System Track Data

ASTERIX stands for All Purpose Structured Eurocontrol Surveillance Information Exchange. It is an ATM surveillance data binary messaging format which allows transmission of information between any surveillance and automation system [37]. ASTERIX defines the structure of the data to be exchanged over a communication medium, from the encoding of every bit of information up to the organization of the data in data blocks. Therefore, the philosophy of ASTERIX can be characterized in two short phrases:

"Distribute everything as required" and "Do not transmit more than necessary."

ASTERIX is a Eurocontrol standard which refers to the presentation and application layers (layers 6 and 7) as defined by the Open Systems Interconnection Reference Model. For the transmission of information related to a specific application, data items are grouped in ASTERIX Categories. Up to 256 categories can be defined. The most interesting category for track exchange is ASTERIX Category 062: System Track Data¹ [38]. The layout of a Cat 062 data block is shown in Table 5-1. A record, in turn, has the layout as shown in Table 5-2, where Data Category CAT = 062 indicates the data block contains system track data; Length Indicator *LEN* indicates the total length of the data block, including the *CAT* and *LEN* field. Then records follow up, until the length of the *LEN* field is reached. In a record, the Field Specification (FPSEC) indicates with flags the data fields comprised. This does not necessary determine the record length, data field extensions can be applied along the way. The relevant data items in Cat 062, either for connectivity or the radar tracker analysis in Section 4-1, are listed in Table 5-3.

¹ASTERIX Category 062: System Track Data is abbreviated to Cat 062.

Data item	Description
IO62/040	Track Number
IO62/060	Track Mode 3/A
IO62/070	Time of Track Information
IO62/105	Calculated Track Position (WGS84)
IO62/130	Calculated Track Geometric Altitude
IO62/185	Calculated Track Velocity (Cartesian)
IO62/220	Calculated Rate of Climb/Descent
IO62/245	Target Identification
IO62/500	Estimated Accuracies

Fable 5-3: Relevant Cat 062 data items for connectivity of the radar tracker an	aly	sis
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It is denoted in Subsection 1-3-1 that the MASE hardly supports modifications, while Subsection 1-3-2 states opportunities exist to meet the requirements for data presentation. Data

FSPEC $ $ F	ield 1 (De	ata iten	p p)	Field	2 (Data i	$tem q) \mid H$	Field 3 (Date	ı iten	1 t)
the treeker	0.001170.011	atudu	data	itom	1060/500	Fatimata	1 a coura oi co	hog	the

Table 5-2: Layout of a Cat 062 record [38].

In the tracker accuracy study, data item I062/500 Estimated accuracies has the main focus. I062/500 contains estimated standard deviations of track position (Cartesian and WGS84), track velocity (Cartesian), track acceleration (Cartesian) and geometric and barometric altitude. In state information exchange, the primary data items are track number, target identification, track position in latitude and longitude, track geometric altitude and track velocity. The calculated rate of climb/descent is used in combination with track velocity to compute the flight path angle.

The Cat 062 processing script is written in the programming language C, as an extension to an existing DUT script for airport surface operations. In this script MEX-files are used. MEX-files provide a way to call custom C routines directly from MATLAB, as if they were MATLAB built-in functions. For the analysis of the estimated accuracy MATLAB has effective support for matrix operations, while C has a fast processing time. The requisite for the Cat 062 processing script is basically no more than the Eurocontrol ASTERIX Cat 062 specification sheet. On the other hand, the efficiency, mentioned in the second phrase, still makes the script extensive. Withal, the use of Field Extension Indicators FXs requires the script to be complete at all times, to avoid single or multiple erroneous byte shift in the bit stream.

To conclude, with the processing capability of Cat 062, connectivity requirements (1) and (2) are met. The chapter continues with the design and implementation of data integration.

Table 5-1: Layout of a Cat 062 data block [38].

Record

Record-1

Record-k

CAT=062

Data integration platform

LEN

5-2

integration is considered:

- On the MASE;
- Stand-alone;
- On the video level.

The MASE hardly supports modifications, because it is evolved legacy software, in a specific programming language, with security restrictions, and unknown available computational power. On the contrary, a stand-alone solution provides freedom in programming language, with no adjustments to the operational environment, and less restricted computational power. Moreover, one of the requirement is UAV GNSS state information, which is not available in the MASE. A stand-alone solution next to the MASE, however, does not support a conformal integration of conflict probing. Alternatively, an integration on the video level accomplishes a conformally integrated display, with freedom in design. Moreover, the operational environment is not impacted.

To provide ATC with UAV support a video overlay is generated over the MASE. A standalone computer processes surveillance tracker data and the UAV GNSS state information. The resulting UAV position indication and conflict zones are built up on a video frame. The video frames of the MASE and the stand-alone computer are digitally combined and displayed on PPI. As a result, the complete common ATC environment is available, independently enhanced with relevant UAV support.

The data integration platform is based on the former DUT research UCS. This research simulator has conflict probing implemented already. Moreover, it has the capability to simulate a UAV with trajectory support. Therefore, the UAV is simulated on the stand-alone computer. This does not mean the system is dependent on a simulated UAV, because, as soon as GNSS position is comprised in surveillance trackers, conflict probing can be applied to any other aircraft in the same manner. Trajectory information, on the other hand, is not implemented up to TRL 6. The system architecture enabled a trajectory depiction by chance. Outside the UAV simulation, it is not supported for other aircraft. For this research, it is not considered a system component, however, the potential is demonstrated in a relevant scenario.

To represent the simulated position of the UAV, an aircraft symbol can be depicted. Also, a rather simple 2D trajectory can be depicted. Obviously, the display perspective is ownship-referenced. Changes to this perspective are described in Section 5-3. The integration of conflict probing and the UAV simulator on one stand-alone computer already meets requirement (3).

In the next subsection, video overlay capabilities of dedicated hardware and computer hardware in combination with software are studied. After that, a configuration that best meets the data integration requirements is defined.

5-2-1 Dedicated hardware

To realize an evolutionary video overlay, dedicated hardware solutions are first analyzed. AOCS Nieuw Milligen uses the Sun XVR-100 Graphics Accelerator [39] to generate the video

Horizontal pixels	1280 1024
Color depth	1024 24 bits
Refresh rate	$10 \mathrm{~Hz}$
Raw bit rate	$315 \mathrm{MB/s}$

Table 5-4: Estimated raw bit rate on the video capture card interface.

Table 5-5:	Estimated	transfer	rates	in	modern	computer	architectures.

Processor turbo frequency	$3.8~\mathrm{GHz}$
DDR3 transfer rate (100 MHz)	8 GB/s
SATA revision 2.0 bus transfer rate	$3 \; {\rm Gbit/s}$
PCI express 2.0 transfer rate (per lane)	$500 \ \mathrm{MB/s}$

output digitally. The maximum supported screen resolution for the Digital Video Interface (DVI) port is 1280 by 1024 pixels (24 bit color depth, refresh rate 60 Hz). In essence, the general performance requirements for video overlay hardware is summarized as:

"Mixing two digital high definition video signals in real-time."

The most effective realization would be in dedicated, standalone hardware. A common hardware video mixing method utilizes chroma keying. Chroma key compositing, its full name, is a special effect for compositing, which means layering, two images or video signals together. This technique is heavily used to remove a background from a photo or video. A color range in the top layer is made transparent, revealing another image behind.

Dedicated standalone hardware exists, but it does not comply to the general performance requirement. There is no dedicated solution that operates digitally and on full HD video. Professional solutions as part of all-in-one video editor platforms exist, but these are too expensive for one specific need. Furthermore, the standards used in professional video editing industry are incompatible with DVI/HDMI needed for ordinary digital computer monitors. The standards used is Serial digital interface (SDI), which is an coaxial interface that transmits uncompressed video signals serially. The required conversions make the solution even more costly. The focus must be shifted to computer hardware, controlled by custom software.

5-2-2 Computer hardware and software

For computer hardware, it is again important to look out for DVI or HDMI, which are similar protocols, and not to explore SDI solutions. None of the digital HD solutions has software included that enables live color keying. Some can for SD video, others can do live color keying, but only with fixed templates and not in combination with a second video feed. Thus, a computer hardware solution is needed for video capturing. After that, the mixing stage is designed and implemented.

The computer architecture needs careful attention for use with video encoding, particularly for HD applications, which are most affected by CPU performance, number of CPU cores, and

certain motherboard characteristics that heavily influence video capture performance. The term video capture, as used in this documentation, describes any application where video is received from a hardware device.

As a starting point, a straightforward calculation is made for the raw bitrate in Table 5-4. Based on the radar sweep time of 4.8 seconds, a 10 Hz screen refresh rate fulfills. For this raw bit rate, the computer's hardware is studied for possible architectural bottlenecks in Table 5-5. From the data in Table 5-5 it is concluded that compared to the maximum video bitrate, the PCIe single lane transfer rate is the bottleneck in the computer architecture, but with a factor two above the estimated raw bit rate for video capturing. The hardware for the PCIe slot is selected accordingly. The modern computer architectures are feasible, now the requirements for the video capture card are listed.

As industry is mainly focused on television or video camera capturing, usually in widescreen (aspect ratio 16:9) resolutions, direct attention is paid to customizable resolutions, in any aspect ratio. For handling video, DirectX, a well-understood Application Programming Interface (API) within the research group, is required. Also, a comprehensive Software Development Kit (SDK) to assign card specific functions, is required. The resulting criteria for hardware are defined as follows:

- Full HD capture support (1920x1080/1080p);
- Computer aspect ratio support;
- DirectX support;
- Software development kit available.

The subsequent video capture card from Electronic Modular Solutions Ltd. (EMS) qualifies best to the four criteria. The card is described in Table 5-6, and depicted in Figure 5-2.

5-2-3 Video overlay solution

In the hardware and software configuration, the mixing should be performed in real-time. For the sake of clarity, the two video signals are first described. The first is the captured signal from the MASE. The second is the locally build video signal with the support information. Normally, the captured video is loaded as background on the stand-alone computer and the support information is drawn on top. This way, the captured video can be loaded right from the memory, without processing. Alternatively, the captured video is displayed directly into a screen filling application, using the EMS DirectShow API. SDK. The support information is then drawn on top using a technique called alpha key compositing. Alpha keying is the process of combining an image with a background to create the appearance of partial or full transparency. In order to combine these video frames correctly, it is necessary to keep an associated alpha channel for each element. This channel contains the coverage information the shape of the geometry being drawn - making it possible to distinguish between parts of the image where the geometry was actually drawn and other parts of the image which are empty. The background of the stand-alone computer gets its alpha channel element active, meaning it will appear transparent. This technique is natively supported in Microsoft Windows.

The alternative direct video display is designed, enabled by a by EMS provided application. This application features custom resolutions, no windows and no borders, basically appearing



Figure 5-2: EMS XtremeRGB-Ex1 video capture card [40].

as a background. The application addresses the capture card efficiently with DirectShow. In the support information video layer an additional color element has to be added, the alpha layer. Additionally, this extra element enables the support information video layer to have a small transparency, making the support information less disruptive overall.

To conclude, data integration requirement (3) is met, after (4), (5) and (6) were already met in Chapter 4. Finally, the design and implementation of data presentation is described.

5-3 Data presentation on the PPI

To overcome the differences addressed in Subsection 3-3, in this section the different depiction is designed and implemented. A PPI displays relative positions of aircraft. The reference is usually the ATC site, but can be basically any location. The data integration platform also operates on relative positions, and prepares the overlay accordingly. It is of major importance to choose the same reference for both displays, and also to keep the reference identical. First, the video layer mapping is studied. Then, a closer look is taken at the projection of maps and aircraft, for more precise mapping.

5-3-1 Video layer mapping

For conformal mapping, it is important to design controls to map the MASE layer and the video overlay correctly. A controller might move the map in duty, although controllers say they do not move the map very often during their shifts. A controller might also change the map scale, by zooming in into the map, to improve his situation awareness. Ideally, the support layer controls are connected to the map controls of MASE. Yet extensions to MASE are hard to realize, and this effort is not beneficial for a demonstrator only.

The stand-alone computer includes support for the initial calibration. Afterwards, it is

Board Format	PCI-e x4 low profile card, 68.9mm x 167.6mm
	PCI-e bus master with scatter gather DMA pro-
	viding maximum data rate of 480Mb/s
Connectors	ONE DVI-I type connectors
Maximum Sample Rate	170Mpixels per second analog RGB or 165 MHz
	DVI Analog modes up to 340MHz pixel clock
	can be captured using dual-pass sampling
RGB	24 bits per pixel / 8-8-8 format
Video Capture Memory	32 MB, triple buffered
DVI Single Link Mode Support	640 x 480, 800 x 600, 1024 x 768, 1280 x 1024,
	$1600 \ge 1200, 1920 \ge 1080, custom modes (HDCP)$
	not supported)
Input Mode Detection	Automatic detection of input modes in hard-
	ware, enabling the tracking of mode changes in
	the source signal. Pixel Output Formats: RGB:
	5-5-5, 5-6-5 or 8-8-8 pixels. YUV: 4:2:2, UYVY,
	YUY2, YVYU
Update Rate	User defined, typically 60 frames per second,
	limited by available PCI-Express bandwidth
	max 480MB/s. TripleI-buffered to eliminate
	tearing artifacts

Table 5-6: Specifications of the EMS XtremeRGB-Ex1 video capture card [40]

assumed the view is fixed. The calibration starts with determining the reference point in latitude and longitude. Then a reference grid will assist in the precise mapping in scale of the support layer on the MASE layer. The resolution of the grid is 1/6 degree latitude and longitude on the overlay, and 1 degree on the MASE. The keyboard enables to zoom in and out, with adjustable step sizes. A screenshot of the calibration process, is shown in Figure 5-3. Here, the dense grid is the overlay grid, and the other grid is the MASE standard grid. The Dutch borders are highlighted in blue on MASE. The overlay uses white contours of the Digital Feature Analysis Data (DFAD) map of the Netherlands, which can be distinguished clearly. Although they are mapped quite well, the originals are not equivalent; one of them either makes simplifications internally or is outdated.

5-3-2 Map projection

Another issue is the projection of DFADs and aircraft on a map. A map projection in this context is the method of representing the surface of the three-dimensional earth on a plane. Map projections are necessary to create these maps. All map projections distort the surface in some fashion. Depending on the purpose of the map, some distortions are acceptable and others are not. Therefore, different map projections exist in order to preserve some properties of the sphere-like body at the expense of other properties. Here, the map projection used by ASTERIX Cat 062, the MASE and the DUT research UCS are studied. In the end, one standard is adopted.

ASTERIX Cat 062 "When the exported calculated position is expressed in a 2D Cartesian



Figure 5-3: MASE overlay calibration process with reference grids and DFAD maps.

coordinate system, a projection is performed on a plane tangential to the WGS-84 Ellipsoid at the location of the reference point. The Y-axis points to the geographical north at that position. The X-axis is perpendicular to the Y-axis and points to the east. The X, Y coordinates are calculated using a suitable projection technique for the final 3D to 2D conversion (e.g. a stereographical projection)"[38].

- **MASE** "The projection, used for all geographical area displays including background maps, shall be according to the conformal conical projection with two standard parallels (Lambert). Geographical position computations of MASE data shall be correct in any part of the northern hemisphere of the world. The display of the geographical area shall be oriented to true north at all times" [41].
- **DUT research UCS** The DUT research UCS is compliant with latitude and longitude coordinates as input. Internally, however, it has not implemented WGS84, but uses local coordinates instead.

For conformance in projection according to data presentation requirements, the Lambert conformal conic (LCC) projection is implemented into the DUT research UCS. The LCC is a conic map projection, which is often used for aeronautical charts. This is probably because the LCC compared to other projections, preserves the ellipsoid locally well. In essence, the projection seats a cone over the sphere of the Earth and projects conformally onto the cone. The cone is unrolled, and the parallel touching the sphere is assigned unitary scale in the simple case. This parallel is called the standard parallel. The conic nature is best seen in Figure 5-4. Pilots favor these charts because a straight line drawn on a Lambert conformal conic projection approximates a great-circle route between endpoints as long as distances

are limited. The European Environment Agency recommends its usage for conformal pan-European mapping at scales smaller or equal to 1:500,000 [42].

The standard parallels in the MASE are predetermined. A trial shows that they do not change by zooming in or out. The latitude coordinates of the standard parallels cannot be extracted from the MASE. This question has been forwarded to the NATO Programming Center, which did not respond before the final version of this thesis. In the meantime the DUT research UCS has variable standard parallels, by default set to 40 and 60 degrees latitude.



Figure 5-4: Lambert conformal conic projection.

To conclude, with the design and implementation of LCC projection on the stand-alone computer, and the manual mapping capability, the requirements (7) and (8) are met. In the final section, a system overview is provided.

5-4 System overview

In Figure 5-5 a system overview is given. Referring to the objective of this thesis, connectivity, data integration and data presentation are distinguished. Elements belonging to connectivity, like the MASE and the DUT research UCS, are located in the red area. Data integration, with the integration platform, is located in the blue area, and data presentation, with the video overlay, is located in the green area. The realized elements are colored black. The simulated elements are colored blue. The realized elements lead to TRL 6, which means that at least the system components have been tested thoroughly in a relevant environment. In TRL 6 they are integrated into a prototype that is near the desired configuration in terms of performance. This setup is tested and demonstrated in the next chapter.



Figure 5-5: Schematic system overview illustrating connectivity, data integration and data presentation aspects. The realized elements are colored black. The simulated elements are colored blue. The realized elements lead to TRL 6.

Chapter 6

Testing and demonstration

After the system is designed and implemented completely, connectivity and data presentation are tested in a relevant environment. The testing of the video overlay on the MASE PPI is described for a real-time ARTAS feed as input. Then, the advantages of the system are illustrated with four relevant scenarios.

6-1 Testing on the MASE

Before demonstrations are performed on the MASE, connectivity and data presentation are tested with external input from ARTAS and output on the MASE at AOCS NM. For connectivity, the ASTERIX processor is fully tested for the ARTAS export in Chapter 4. In that study, 2,600,000 records were processed without errors. The records were double checked for used data item assignment in AsterixInspector [43], an open-source tool that reads multiple ASTERIX categories and displays data blocks and records in a graphical user interface. The difference with the real-time situation in the MASE, with either playbacked or live traffic, is that the ASTERIX data blocks are not read from a binary file, but are received in packages over UDP multicast. The performance with this network protocol is tested at AOCS Nieuw Milligen. A performance comparison showed that approximately 300 tracks were maintained with an update frequency of 50 to 60 tracks per second. The RNLAF confirmed the number of active tracks, and confirmed an usual update time of 4.8 seconds per track.

For data presentation, the mapping and projection are tested for conformance with a calibration. The calibration starts with a definition of the map position and map resolution within the MASE software, e.g. to exclude the top border. An initial overlay depiction before calibration is shown in Figure 6-1. For example, the yellow NOTAM aras next to the province of Noord-Holland clearly illustrate the current mismatch. Also, the vertical grid lines demonstrate a deviation from North to South, indicating a projection mismatch. To calibrate, reference grids, DFAD contours and NOTAM areas are used as references to achieve a conformal zoom level, map center shift and projection configuration.

Furthermore, the projection of ARTAS traffic is tested for conformance with the MASE traffic depiction. Differences here would also impact the conflict zone depiction. ASTERIX Cat 062 as the civil standard for track data exchange, is not yet supported by the MASE,



Figure 6-1: Initial calibration of the video overlay on the MASE, where zoom level, map center and projection parameters need refinement.

which is at AOCS Nieuw Milligen used only for air surveillance and fighter control. Cat 062 compatibility is expected in May 2012. Nevertheless, recorded and live ARTAS streams also contain ASTERIX Cat 048 Monoradar Target Reports. This raw radar plots from five different radar sites are trackable by the MASE tracker. In other words, in the integration, the same radar sources are tracked by two different radar trackers. When radar tracks from both sources are depicted, the air picture looks like Figure 6-2. The ARTAS traffic is depicted as a cyan aircraft symbol. The MASE tracker depicts plots, including a history of plots, and depicts a white diamond for each identified track in Dutch airspace. A label furthermore indicates SSR coverage. It is concluded that most tracks correlate, with exceptions of unidentified tracks for both trackers. These exceptions could not be explained by the RNLAF, but will not impact the demonstration significantly.

6-2 Concept demonstrator

Following the test of the full system concept, this section illustrates the advantages of the concept using several relevant traffic conflict scenarios involving unmanned and manned aircraft. Given that UAVs have unfamiliar performance characteristics, and perform unfamiliar flight patterns, a spatially integrated depiction of airspace where a future loss of separation is predicted, can help to preserve safety in classes of airspace that accommodate both manned and unmanned aircraft.



Figure 6-2: Correlation of the ARTAS tracker (cyan aircraft symbols) and the MASE tracker (white diamonds) with exceptions of unidentified tracks on both sides.

In this test, the UAV is being simulated, while traffic is being replayed from a recorded air picture at AOCS NM. The UAV is controlled and positioned with latitude, longitude, altitude, heading and velocity. Traffic comes as it is, since it cannot be controlled. The resulting depiction is studied on the DUT research ATC simulator, while the target system is the MASE. The MASE is NATO classified and therefore only accessible on AOCS NM. Meanwhile, scenario preparation was done at DUT.

The upcoming scenarios illustrate several aspects of conflict probing. The first scenario illustrates how conflict probing can assists with detecting a conflict and providing information on the effect of changes to the current state in busy airspace. After that, a more complex conflict scenario illustrates the impact of a maneuver on future separation with all other traffic. Next to providing informations about potential missed detections, conflict probing can also provide information about potential unnecessary maneuvers. The third scenario illustrates a potential unnecessary maneuver, or false alarm. Finally, a scenario is presented where the combined effect of trajectory information and conflict probing is illustrated.

6-2-1 Scenario 1: Assessing prevention maneuvers for unfamiliar aircraft

In the first scenario, a relatively slow UAV is returning from the province of Friesland for a surveillance mission in the context of the Elfstedentocht, a popular sports event in the Netherlands. The UAV is descending from his cruise altitude, and it seems clear of traffic until it crosses a common air route for arrival and departure traffic for Amsterdam Airport Schiphol. With conflict probing, the future conflict is detected. Moreover, all prevention maneuvers are assessed on future separation.

In Figure 6-3, the situation without conflict probing is shown. In the experimental stage of UAVs in non-segregated airspace, controllers are unfamiliar with the UAV's flight performance. Therefore, a controller can hardly predict whether its descent profile will intersect with arriving traffic from Amsterdam Airport Schiphol. As soon as the controller detects that the descent profiles are catching up, he has no information about an efficient prevention maneuver.

In Figure 6-4, the situation with conflict probing is shown. Conflict probing can aid in detecting the conflict, but also provides information on the effect of changes to the current state. Here, the controller is informed that the descent profiles of UAV and LCO1506, departing from Schiphol, will conflict. Also, conflict probing assesses all prevention maneuvers on future separation. With this information, the controller can be sure which prevention maneuvers prevent the future conflict definitely.

6-2-2 Scenario 2: Impact of a maneuver on future separation with other traffic

In the second scenario, a relatively slow UAV heads for a search and rescue mission at the IJsselmeer. On its way at cruise altitude it approaches a KLM aircraft on a standard instrument departure to the East. At the same Flight Level, there is another KLM aircraft behind. The performance characteristics between the manned aircraft and the UAV differ much, that might result in unintentional overtaking. Conflict probing provides not only information about the future separation with the intruder after maneuvering, it also provides



Figure 6-3: Scenario 1. The yet unfamiliar flight performance of the UAV makes conflict prediction for controllers harder. As a result, it is difficult to detect that the descent profiles of *UAV* and *LCO1506* will result in a conflict.



Figure 6-4: Scenario 1. Conflict probing aids in detecting the future conflict between *UAV* and *LCO1506*, but also assesses all prevention maneuvers in the busy airspace on future separation.

information about the future separation with all aircraft after maneuvering. Hence, with conflict probing a prevention maneuver will not lead to a new conflict with another aircraft.

In Figure 6-5, the initial situation is given. KLM1977 is the aircraft on a collision course with the UAV. A lateral maneuver to the right prevents this future conflict from occurring, at first sight leaving aircraft KLM30Y behind. Because of the unfamiliar flight performance of the UAV, an unexpected conflict with a greater extent than the initial conflict is about to occur, that may come unnoticed.

In Figure 6-6, the situation with conflict probes is shown. Maintaining track leads to a conflict with KLM1977. According to the conflict zone, the smallest track angle to prevent the conflict is to the right. However, the larger velocity of the KLM30Y causes this aircraft to catch up. Thanks to the complete conflict assessment including all traffic within the look-ahead time, it becomes clear that this conflict can only be prevented with a significant change of track, or with a change of flight level. This shows conflict probing provides support effectively, a prevention maneuver does not lead to a new conflict. Besides that, it provides support efficiently, because the complete conflict assessment provides sufficient information to select a prevention maneuver that is clear of future conflicts with all traffic.



Figure 6-5: Scenario 2. UAV and *KLM1977* are on a collision course. A maneuver to the right will prevent loss of separation, and will apparently keep *KLM30Y* behind.



Figure 6-6: Scenario 2. The same situation with conflict probing enabled, informs the controller about a second conflict with an even greater extent. The advantage of the spatially integrated depiction is that it provides information about how a change of track impacts future separation with all aircraft involved.
6-2-3 Scenario 3: Avoid unnecessary maneuvers

In the third scenario, *UAV* returns from a mission and heads to Leeuwarden airbase on a slow descent profile. On its course, it closes inbound traffic to Amsterdam Airport Schiphol on about the same Flight Level from the right. Where a controller predicts future separation on the rather safe side, conflict probing tells about the precise future separation. In this scenario the advantage is that an accurate prediction shows that no conflict will occur. Compared to other scenarios, this scenario illustrates a scenario that is likely to result in a unnecessary maneuver, also called a false alarm.

In Figure 6-7, the UAV flies on FL154 and detects *KLM1976* approaching from the right on FL163, heading for initial approach fix ARTIP at the boundary of the Schiphol Terminal Area. It is on beforehand clear that the manned aircraft has a larger velocity. However, in this case of a separation close to the ANSD, the controller rather avoids the risk of a loss of separation and instructs a maneuver.

In Figure 6-8, the same situation is illustrated, but with conflict probing enabled. With conflict probing, it immediately becomes clear that no action is required, because the current track is free of future conflicts. Nevertheless, the spatially integrated depiction does inform the controller that a maneuver to the left causes a conflict, and a maneuver to the right enlarges future separation. Intuitively, this maneuver would worsen the situation, while in reality it does not. Conflict probing avoids unnecessary maneuvers, but keeps providing readily actionable information in case circumstances change.

6-2-4 Scenario 4: Combined effect of conflict probing and trajectory information

In the fourth scenario, UAV is deployed for remote sensing of the channel depth at the Port of Rotterdam. Therefore, a trajectory has been exchanged with ATC, reaching from the Maasvlakte to the city center. On the optimal sensing altitude of FL100, outbound traffic from Amsterdam Airport Schiphol sometimes intersects the trajectory. The depicted trajectory increases traffic predictability in busy airspace. Conflict probing increases conflict predictability on and around the trajectory. The combination of both limits the false alarm rate, when conflicts are off the trajectory. On the other hand, it also limits missed detection when the focus would be solely on on-track conflicts, and the UAV should suddenly divert.

In Figure 6-9, the situation is shown with conflict probing active. UAV almost approaches the city center with visual on the Waalhaven. The UAV is about to initiate a turn over Rotterdam South. However, here, the controller is only aware of the immense conflict zone ahead, and tends to deconflict the situation.

In Figure 6-10, the situation is shown with conflict probing and trajectory information. In this situation it is imminent that a turn will be requested shortly, and the future conflict disappears. It is, however, useful to provide information about the future separation with traffic for off-track states, since it gives understanding of the traffic situation around the trajectory, which enables rapid action when the circumstances change.



Figure 6-7: Scenario 3. *KLM1976* closely approaches *UAV* from the right in the middle of the ATC screen. It is clear that the manned aircraft has a larger velocity, but it is unclear whether the ANSD is maintained.



Figure 6-8: Scenario 3. The same situation with conflict probing is shown. From the conflict zone depiction, it is immediately clear that no action is required, because current UAV track is free of future conflicts.



Figure 6-9: Scenario 4. The UAV is deployed for remote sensing at the port of Rotterdam. In this busy part of Dutch airspace, departing traffic from Schiphol might intersect the trajectory. The conflict probes predict a conflict ahead. The controller is here not aware the UAV is about to request a turn.



Figure 6-10: Scenario 4. The same situation is depicted, but with trajectory information added. It is imminent that a turn is expected that will result in the future conflict to disappear. The conflict zone depiction is relevant here to give a controller understanding of the traffic situation around the trajectory, when circumstances would change.

Chapter 7

Conclusion and recommendations

This chapter concludes on the research conducted in this thesis. It summarizes the background study and the analysis of near-term opportunities. After that, it describes the resulting integration platform. Finally, the recommendations for further research are listed.

7-1 Conclusion

The objective of this thesis is to provide Air Traffic Control (ATC) with support for level 3 Unmanned Aerial Vehicle (UAV) situation awareness. Therefore, the potential of conflict probing is explored. Exploiting near-term opportunities in the area of connectivity, data integration and data presentation, conflict probing is demonstrated on an existing ATC system. The research leads to an integration into an existing ATC system up to Technology Readiness Level 6.

The difference in nature of manned and unmanned aircraft makes the separation task for air traffic controllers harder. Particularly, in an experimental stage, UAVs demand additional controller effort, because of the uncommon flight dynamics and uncommon flight patterns. A controller should, however, be able to perform the aforementioned tasks in his airspace sector efficiently without restricting other traffic so much that aircraft will be delayed. Conflict probing seems a concept that can be useful in assisting the controller with the early detection of future conflicts, and providing information about prevention maneuvers, relieving controller from the prediction task.

For the implementation, a platform is designed with connectivity and data presentation designed independently from the target ATC system, the Multi-Aegis Site Emulator (MASE). For this, a real-time feed of track information is required, which was available in Eurocontrol's ASTERIX standard at the Royal Netherlands Air Force Air Operations Control Station Nieuw Milligen. The integration platform processes the track information, and then prepares the support information on a video frame. A high definition video capture card captures the MASE video signal, and then places the video frame on top of it. The integrated video signal is displayed on a MASE station. Herewith, a stand-alone system independent integration platform with video overlay, to test innovative ATC/C2 concepts with no impact on the operational environment, is created. The conflict probing function has stringent requirements on position and velocity accuracies to provide support with a limited false alarm rate. Results from an extensive data quality study, which analyzed radar tracker performances from an ATM Surveillance Tracker And Server (ARTAS) shows that track accuracies vary greatly. Holding on to the worst-case accuracy leads to an infeasible concept. With a dynamic accuracy, based on actual sensor performance, for those situations that exceed the worst-case assumption, the false alarm rate is reduced. Accordingly, the Delft University of Technology (DUT) research UAV Control Station, ARTAS, the integration platform and MASE, are successfully tested together for UAV support in several relevant scenarios in a recorded Dutch air picture. With the concept demonstrator, it is illustrated that TRL 6 is reached.

7-2 Recommendations

In this section the recommendations for further research are listed:

- Test and evaluate the conflict probing concept for ATC thoroughly. In the current study, the concept has lead to a concept demonstrator. In further research, controllers can contribute to the concept when they are being actively involved in an evaluation with balanced scenarios with and without conflict probes enabled;
- Explore the integration of trajectory information and conflict probing information. Currently, this is up to the controller. It has additional value to add off-track conflicts. It has even more value to highlight conflicts that will occur on the trajectory after a turn, or a series of turns;
- As soon as 4D-Trajectory Data Link standards come available, it is interesting to extend the DUT research UCS and integration platform with this capability. With this extension, more aircraft can downlink their trajectory. Also, before trajectory negotiation becomes mandatory, benefits exist in terms of predictability;
- Extend the conflict probing concept to more aircraft. In order to do this, Automatic Dependent Surveillance-Broadcast data is required. This extension facilitates the research into bilateral probing and implicit coordination.

Bibliography

- W. Wagner, "Lightning Bugs and other Reconnaissance Drones; The can-do story of Ryan's unmanned spy planes," Armed Forces Journal International, in cooperation with Aero Publishers, Inc., 1982.
- [2] US Department of Defense, "Unmanned Systems Integrated Roadmap 2009-2034," 2009.
- [3] US Department of Defense, "Unmanned Systems Roadmap 2007-2032," 2007.
- [4] M. DeGarmo, "Issues concerning integration of unmanned aerial vehicles in civil airspace," MITRE, Center for Advanced Aviation System Development, McLean, Virginia, 2004.
- [5] Eurocontrol, "Specification for the use of military UAVs as operational air traffic outside segregated airspace," 2007.
- [6] A. Intelligence, "President Obama signs FAA bill into law; work on unmanned integration into airspace, GPS-based air traffic management to begin," Feb.
- [7] FAA, "Evaluation of Candidate Functions for Traffic Alert and Collision Avoidance System II On Unmanned Aircraft System UAS," 2011.
- [8] SESAR Consortium, "The ATM Target Concept," 2007.
- [9] The Joint Planning and Development Office, "Concept of operations for the Next Generation Air Transportation Systems," 2007.
- [10] J. Tadema, A. Goossens, and E. Theunissen, "Applying NEC to UAS Operations Using an Evolutionary Approach," 15th International Command and Control Research and Technology Symposium, Command and Control Research Program (CCRP), 2010.
- [11] J. Tadema and E. Theunissen, "Design and Evaluation of a GUI for operator involvement in Airborne Conflict Detection and Resolution," in *Digital Avionics Systems Conference*, 2008. DASC 2008. IEEE/AIAA 27th, p. 5A, IEEE, 2008.
- [12] T. Rand and M. Eby, "Algorithms for airborne conflict detection, prevention, and resolution," 2004.

- [13] J. Tadema, E. Theunissen, R. Rademaker, and M. de Haag, "Evaluating the impact of sensor data uncertainty and maneuver uncertainty in a conflict probe," in *Digital Avionics Systems Conference (DASC)*, 2010 IEEE/AIAA 29th, pp. 4–C, IEEE, 2010.
- [14] US Department of Defense, "Technology Readiness Assessment Guidance," 2011.
- [15] FAA, "Order JO 7110.65U Air Traffic Control," 2011.
- [16] J. Tadema, Unmanned Aircraft Systems HMI and Automation: Tackling Control, Integrity and Integration Issues. Shaker Publishing BV.
- [17] S. Thompson, J. Andrews, C. Harris, and K. Sinclair, "Required Surveillance Performance Accuracy to Support 3-Mile and 5-Mile Separation in the National Airspace System," 2006.
- [18] US Department of Transportation, "Vulnerability Assessment of the Transportation Infrastructure Relying on GPS," 2001.
- [19] G. Koeners, M. De Vries, A. Goossens, J. Tadema, and E. Theunissen, "Exploring Network Enabled Airspace Integration functions for a UAV Mission Management Station," in 25th Digital Avionics Systems Conference, 2006 IEEE/AIAA, pp. 1–11, IEEE, 2006.
- [20] W. Stamper, "Understanding Mode S Technology," Defense Electronics/rfdesign. com, pp. 18–19.
- [21] R. Weibel and M. Jenkins, "Automatic Dependent Surveillance-Broadcast (ADS-B) Costs, Benefits, Applications, and Implementation Challenges," 2008.
- [22] E. Theunissen, A. Goossens, O. Bleeker, and G. Koeners, "UAV mission management functions to support integration in a strategic and tactical ATC and C2 environment," in *Proceedings of the AIAA Modeling and Simulation Technologies Conference, San Francisco, California*, 2005.
- [23] Eurocontrol, "Controller-Pilot Datalink Communications," Apr. 2011.
- [24] H. Erzberger, "Transforming the NAS: The next generation air traffic control system," in 24th International Congress of the Aeronautical Sciences, Yokohama, Japan, Citeseer, 2005.
- [25] J. Klooster, S. Torres, D. Earman, M. Castillo-Effen, R. Subbu, L. Kammer, D. Chan, and T. Tomlinson, "Trajectory synchronization and negotiation in Trajectory Based Operations," in *Digital Avionics Systems Conference (DASC)*, 2010 IEEE/AIAA 29th, pp. 1–A, IEEE.
- [26] M. Jackson, "Role of Avionics in Trajectory-based Operations," Aerospace and Electronic Systems Magazine, IEEE, vol. 25, pp. 12–19, july 2010.
- [27] L. Thomas, C. Wickens, and E. Rantanen, "Imperfect automation in aviation traffic alerts: A review of conflict detection algorithms and their implications for human factors research," in *Human Factors and Ergonomics Society Annual Meeting Proceedings*, vol. 47, pp. 344–347, Human Factors and Ergonomics Society, 2003.

- [28] K. Chase and B. Tiblin, "INCAS Integrated Navigation and Collision Avoidance System," Navigation: journal of the Institute of Navigation, vol. 18, no. 2, 1971.
- [29] J. Tadema, E. Theunissen, and K. Kirk, "Self Separation Support for UAS," in Proceedings of the AIAA Infotech@ Aerospace Conference 2010, American Institute of Aeronautics and Astronautics, 2010.
- [30] A. Zeitlin and M. McLaughlin, "Safety of cooperative collision avoidance for unmanned aircraft," 2006.
- [31] E. Theunissen and M. Uijt de Haag, "Towards a seamless integration of awareness support and alerting system: why and how," 2011.
- [32] J. Tadema, E. Theunissen, and T. Lambregts, "Exploring the potential of energy and terrain awareness information in a Synthetic Vision display for UAV control," in *Proc.* of SPIE Vol, vol. 7328, pp. 732809–1. even more on const functions, focus on terrain.
- [33] RTCA, "Minimum Operational Performance Requirements (MOPS) for Aircraft Surveillance Application Systems (ASAS)," 2009.
- [34] FAA, "ADS-B Out Performance Requirements To Support ATC Service; Final rule," 2010.
- [35] NATO Programming Centre, "Interactive Simulation Package (ISP)," Feb. 2011.
- [36] IEEE Standards, "1278.1a-1998 Distributed Interactive Simulation Application Protocols," 1998.
- [37] Eurocontrol, "ASTERIX Project," Jan. 2012.
- [38] Eurocontrol, "Standard for Surveillance Data Exchange Part 9: ASTERIX Category 062," 2011.
- [39] Sun Microsystems, "XVR-100 Graphics Accelerator HD15 Video Formats," July 2011.
- [40] EMS, "XtremeRGB-Ex1," Oct. 2011.
- [41] NATO, "SMASY-401-SRS (unrestricted),"
- [42] JRC-Institute for Environment and Sustainability, "Short Proceedings of the 1st European Workshop on Reference Grids," 2003.
- [43] V. Poplawski, "Asterixinspector 0.7.3," Oct. 2011.

Glossary

List of Acronyms

4DT	4D Trajectory
4DTRAD	4D Trajectory Datalink Services
AAC	Advanced Airspace Concept
ACAS	Aircraft Communications Addressing and Reporting System
ACCS	NATO Air Command and Control System
ADS-B	Automatic Dependent Surveillance-Broadcast
ANSD	Assured Normal Separation Distance
ANSP	Air Navigation Service Provider
AOCS	Air Operations Control Station
ΑΡΙ	Application Programming Interface
ARTAS	ATM SuRveillance Tracker And Server
ASAS	Aircraft Surveillance Application Systems
ASTERIX	All Purpose STructured Eurocontrol SuRveillance Information Exchange
АТС	Air Traffic Control
АТМ	Air Traffic Management
ATN	Aeronautical Telecommunications Network
C2	Command and Control
CDTI	Cockpit Display of Traffic Information
COA	Certificate Of Authorization
CPDLC	Controller Pilot Data Link Communication

DFAD	Digital Feature Analysis Data
DIS	Distributed Interactive Simulation
DSA	Detect, Sense and Avoid
DUT	Delft University of Technology
DVI	Digital Video Interface
EFB	Electronic Flight Bag
EUROCAE	European Organisation for Civil Aviation Equipment
FA	False Alarm
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
GCS	Ground Control Station
GNSS	Global Navigation Satellite Systems
HDMI	High-Definition Multimedia Interface
ISP	Interactive Simulation Package
LCC	Lambert Conformal Conical Projection
LOA	Level of Authority
MALE	Medium Altitude Long Endurance
MASE	Multi-Aegis Site Emulator
NACp	Navigation Accuracy Categories for Position
NACv	Navigation Accuracy Categories for Velocity
ND	Navigation Display
NEC	Network Enabled Capability
NextGen	Next Generation Air Transportation System
PFD	Primary Flight Display
PPI	Plan Position Indicator
RNLAF	Royal Netherlands Air Force
RTCA	Radio Technical Commission for Aeronautics
SA	Situation Awareness
SDI	Serial Digital Interface

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SDK	Software Development Kit
SESAR	Single European Sky ATM Research
SWIM	System Wide Information Management
тво	Trajectory-based Operations
TCAS	Traffic Collision Avoidance System
TRL	Technology Readiness Level
TASFE	Tactical Separation Assured Flight Environment
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UCS	UAV Control Station
