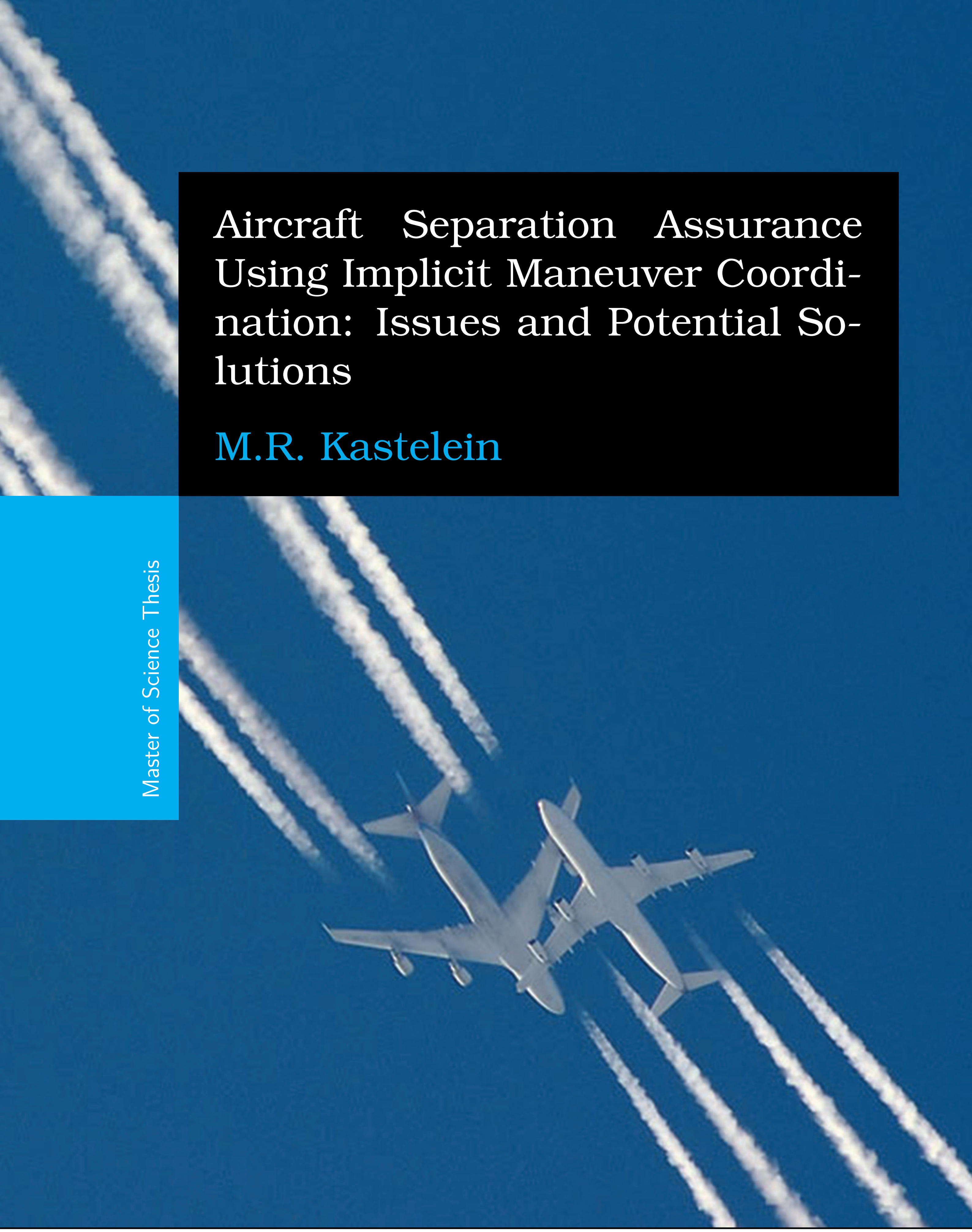
Aircraft Separation Assurance Using Implicit Maneuver Coordination: Issues and Potential Solutions

M.R. Kastelein

Master of Science Thesis



TU Delft Delft University of Technology

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

M.R. Kastelein

July 1, 2013

Faculty of Electrical Engineering, Mathematics and Computer Science · Delft University of Technology

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The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled

Aircraft Separation Assurance Using Implicit Maneuver Coordination: Issues and Potential Solutions

by

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in partial fulfillment of the requirements for the degree of

Master of Science Electrical Engineering

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Abstract

In earlier research projects, the depiction of airspace in which a loss of separation is predicted to occur has been explored as a means to increase conflict awareness. The computation of the conflict space is based on the current state of traffic and ownship. If the traffic maneuvers, the location and extent of the conflict space will change accordingly. Hence, if the other traffic also maneuvers to avoid the predicted loss of separation it is of fundamental importance that the maneuvers of ownship and traffic are complementary. To ensure that a conflict will indeed be avoided by such a maneuver and not accidentally made worse when both maneuver simultaneously, a form of coordination is necessary between the aircraft involved. Some research has been done in the area of implicit coordination between two aircraft, which provides coordinated resolution maneuvers to conflicting aircraft based on an epsilon criterion when only state information is periodically broadcast by the aircraft. This thesis explores conflict scenarios that need additional rules to be safely resolved using implicit maneuver coordination and provides possible solutions. Furthermore, a system is developed for the application of implicit maneuver coordination in scenarios that involve multiple intruders. This system is summarized in a decision tree that can be used to categorize scenarios according to the location of the closest point of approach of the intruders and the connectedness of the corresponding conflict areas. These factors determine the scenario complexity and the available or preferred conflict resolution options. The system can be used to support pilots in quickly assessing the most optimal maneuver in complex conflict scenarios, plan aircraft routes, or make preventive maneuvers. Maximum airspace density with implicit maneuver coordination is addressed based on the minimum distance to conflict at which a maneuver must be made to prevent loss of separation.

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The research and the resulting document you are now reading would not have been possible without others. Mainly, I would like to thank my supervisor, Erik Theunissen. His knowledge, experience, and drive for excellence are greatly appreciated. I also thank him for the discussions that always produced the missing pieces and for promptly responding to my questions. Also, I would like to thank Joris Koeners for his input, practical assistance, and opening up his office for me.

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Chapter 1

Introduction

Implicit maneuver coordination is a framework that enables maneuvers performed by pilots to prevent loss of separation to be coordinated, without the use of communication between the aircraft to negotiate the resolution maneuvers. If both aircraft involved in a conflict maneuver, their actions will still be complementary. This is necessary for conflicts to be solved and not made worse. The result of their actions must resolve the conflict.

For increased robustness, implicit maneuver coordination is preferred over explicit coordination. Implicit maneuver coordination eliminates the need for an additional communication system that would be a single point of failure in pilot controlled separation assurance. Implicit coordination can be done based solely on the surveillance data from ADS-B, containing state information of aircraft in the surrounding airspace.

1-1 Background

Airline passenger travel has been increasing for many years and this trend is expected to continue into the future. The number of passengers in the United States is predicted to nearly double in the next 20 years [1], a similar growth is expected in Europe [2]. With current technology, this growth cannot be sustained. Additional runways can be added to airports to accommodate an increase in traffic, but the minimum amount of separation between aircraft is dictated to a large degree by current surveillance technology and limitations in air traffic controller workload. This separation also puts a limit on the number of aircraft in a certain airspace, the volume of space used for air travel. Especially in the airspace surrounding large carrier hubs, this airspace limitation will prevent further growth. In order to lift these limitations and allow air traffic to grow according to demand, new technology must be implemented to safely reduce the separation standards. The system designed for this purpose is NextGen [3, 4] in the US and SESAR [5, 6] in Europe.

1-1-1 NextGen

Instead of relying solely on ground-based radars, a NextGen environment uses GPS to obtain a better position estimate of aircraft. This reduction in uncertainty can enable a decrease in safe aircraft separation margins, thus allowing more aircraft within the same airspace.

With smaller separation margins and the availability of more precise position data, some separation responsibilities are expected to be shifted to the pilot or even the aircraft navigation systems [7], potentially resulting in a lower workload for air traffic control (ATC). Self-separation can be done specifically in the time window between ATC being able to negotiate new trajectories, 10-20 minutes before a conflict, and TCAS issuing a traffic advisory, less than a minute to a projected collision.

1-1-2 Separation Assurance

Currently, separation is assured by ATC. When a collision is imminent, TCAS takes care of collision avoidance. ATC has a complete overview of the aircraft in flight and can therefore easily determine which aircraft should take what maneuver to avoid collision. In case TCAS is triggered, an algorithm determines whether to climb or descend based on surveillance radar data.

If pilots are given responsibility in separation assurance there is also a need for maneuver coordination. This is to ensure the maneuver the pilot chooses solves the conflict and does not decrease the separation between aircraft, increasing the risk of collision. Maneuver coordination can also prevent pilots from choosing an unneeded maneuver or a maneuver that is larger than needed that causes unnecessary deviation from the optimal flight path.

1-2 State of the Art

Previous research by NASA Langley into implicit maneuver coordination [8, 9, 10] has provided a way to verify conflict solving and implicit maneuver coordination properties of an algorithm. This research focused on building a correct mathematical foundation for horizontal and vertical maneuvers.

A review of research into Cockpit Display of Traffic Information concepts is contained in [11]. INRIA and NASA Langley have developed a 3D CD&R algorithm that provides a set of resolution vectors that touch the boundaries of a 3D protected area around the intruder, then selects the optimal solution for ground speed, ground track and / or vertical speed if available.

MITRE is developing a CD&R algorithm NextCAS [12] that implements capability improvements to TCAS for use in a NextGen environment. NextCAS computes six resolution advisories, two solutions for each dimension: ground track, ground speed, and vertical speed. These six solutions are down-selected first based on encounter geometry and then based on ownship preferences and operational considerations to determine the final single solution.

A pilot support concept for self separation based on conflict probing is described in [13]. This concept can provide conflict detection and resolution support with different level of automation.

In [14], a review was conducted of separation assurance and collision avoidance concepts for NextGen. Concepts can be distributed along an asix of responsibility assigned to the controller versus the pilot and on an axis of the degree of automation. The impact of concepts is compared to the current environment and verified for viability.

Research at NASA Ames has been done in the area of ground-based automated separation assurance to alleviate controller workload. This research has resulted in development of the Tactical Separation Assured Flight Environment (TSAFE), that can serve as a backup system duplicating a limited set of safety-critical functions for conflicts predicted to occur within approximately 2 minutes. A new set of vertical conflict resolutions for a conflict aircraft pair is presented in [15]. Also, heuristics are presented for using vertical and horizontal resolution algorithms minimizing interference with TCAS. Finally, an algorithm is discussed for resolving conflicts with multiple aircraft based on prioritization and merging of maneuver sets. New procedures for vertical resolution maneuvers of TSAFE in en route airspace are presented and tested in [16]. [17] describes a new conflict detection algorithm of TSAFE for terminal airspace based on current state information, flight intent, and dynamic separation standards for terminal airspace to deal with excessive false alerts. Effects of conflict resolution automation on controller workload are studied in [18].

Encounter models that can be used to verify conflict resolution algorithms are presented in [19]. Three types of models are discussed: collision geometry encounter models, which describe encounters by the closest point of approach (see section 2-3) and encounter geometry, stochastic encounter models, which are statistically representative of encounters observed in the National Airspace System, and validation encounter models, which are encounters designed to validate simulation results in flight tests. The model used to generate encounters throughout this thesis is a collision geometry model.

1-3 Research Problem

Implicit maneuver coordination has not been considered for exceptional conflict scenarios that can be encountered or for conflict scenarios involving multiple intruders. It is unclear whether these scenarios are covered by the formulated criteria or additional rules are needed to extend the framework to include these cases.

1-4 Thesis Objective

The objective of this thesis is therefore to address the following research questions:

1. What scenarios require special attention when using implicit maneuver coordination?
2. Can implicit maneuver coordination still be used in scenarios with multiple intruders?
3. What additional rules are necessary when solving conflicts that involve multiple intruders by using implicit maneuver coordination?
4. What do these additional rules imply for data processing?

5. What is the maximum airspace traffic density that still allows all conflicts to be solved by using implicit maneuver coordination?

1-5 Thesis Structure

This thesis is outlined as follows. Important key principles will be explained in chapter 2. They are then applied in chapter 3 to analyze two special cases in separation assurance, and in chapter 4 to categorize multiple intruder scenarios and define a rule-based system for solving multiple intruder scenarios using implicit maneuver coordination. Chapter 5 discusses possible methods to implement the categorization algorithm, followed by applications of this research in chapter 6. Finally, the conclusion is presented in chapter 7.

Chapter 2

Key Principles

In order to analyze the research questions posed in section 1-4, some key principles must be understood. The elementary principles of separation and conflict are treated in section 2-1, followed by the concept of conflict probing and the resulting conflict areas in 2-2. Another key principle used in this research is the closest point of approach found in section 2-3. Section 2-4 contains an analysis of the framework of implicit maneuver coordination, a connection is made with conflict probing in 2-5. Finally, assumptions used in this thesis are listed in section 2-6.

2-1 Separation and Conflicts

The minimum distance required between aircraft in en route airspace for safe operation, known as the assured normal separation distance, is typically 5 nm lateral (D) and 2000 ft vertical (H) [20]. This can be visualized as a protected volume around an aircraft (figure 2-1), with double the separation margins as dimensions. When another aircraft, the intruder, enters this volume, there is loss of separation. If a loss of separation is predicted to occur, based on an extrapolation of current flight state of both aircraft, the aircraft are considered to be in conflict.

2-2 Conflict Probing

The information needed to assure separation between aircraft is not in the current location of the intruder in space with respect to ownship. Instead, it is more important to know where in space and at what speed, track and flight angle of ownship loss of separation with an intruder will occur. This can be found by using conflict probes that result in a conflict area for each intruder. A conflict area is the graphical representation of the space that must be avoided to maintain separation with an intruder.

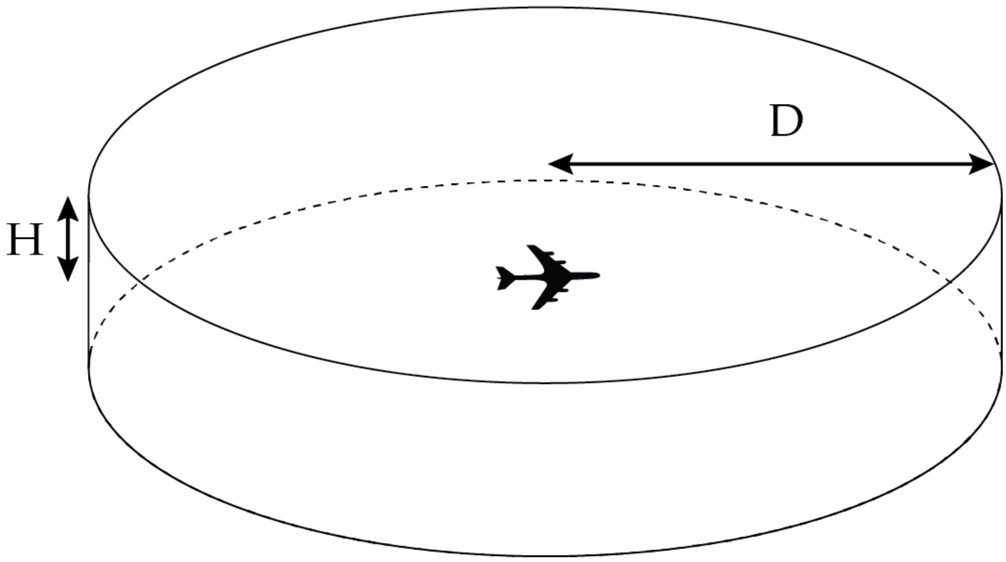

Figure 2-1: Protected Volume Around Aircraft, with Horizontal Separation D and Vertical Separation H

2-2-1 Conflict Area

In a conflict there are two aircraft approaching each other at a certain angle. State information is used to extrapolate the aircraft positions into the future. Test vectors are then created by varying ownship track angle, these are the green vectors shown in figure 2-2. While keeping other variables constant, along the test vectors, together with the current track vector, the separation with the intruder is calculated for ownship flying these headings. For each vector, the points are noted where separation is lost, the distance between the aircraft going below the defined value, and the point where separation is regained, where the distance between aircraft moves again above the minimum distance. These points are shown as yellow dots in figure 2-2. Connecting these points we get the conflict area in the form of an ellipsis, this is shown in figure 2-3. However, it can take on different shapes depending on speed, angle and distance between the aircraft. The test vectors shown in red intersect the conflict area and will lead to a loss of separation. Choosing one of the green vectors on either side will solve the conflict. An example of how conflict areas are displayed on the navigation display in simulations can be found in figure 2-6.

The same process can be used to get a representation of the vertical conflict area by defining test vectors for different ownship flight angles. Combining the track and flight angle ranges, we can calculate all points where loss of separation occurs in 3D from which a spatial conflict space can be drawn.

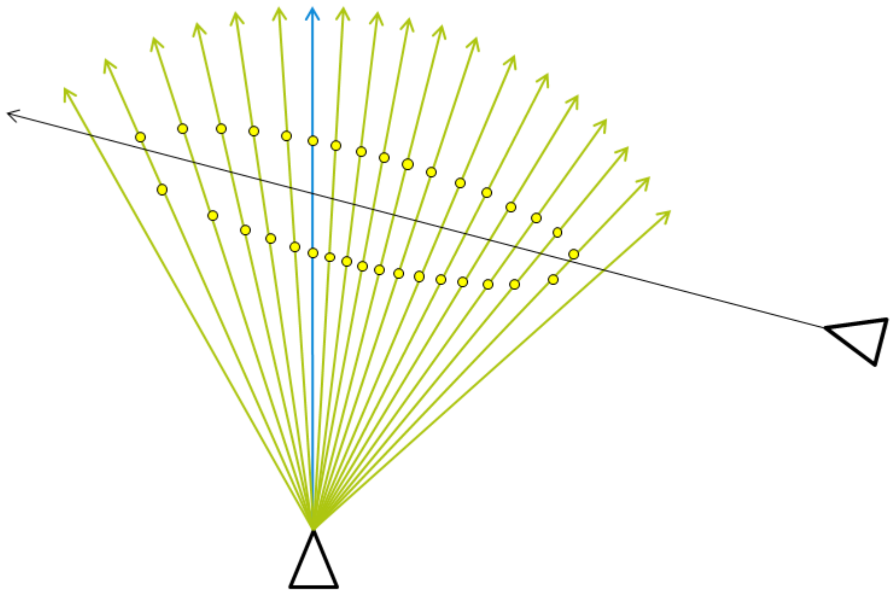

Figure 2-2: Points Where Separation Is Lost and Regained

2-2-2 Speed Changes

Changes in ownship speed can have a large effect on the location of the conflict areas. It is, however, not practical to combine these effects with the effects of variations in track and flight angle, since this would make the conflict areas grow substantially without providing additional insight into the conflict scenario. It would also be unclear which parts of the conflict area are attributed to which changes in speed. What can be used instead is a speed dial that allows the user to set different speed offsets from the actual speed and see how this affects the conflict areas.

2-3 Closest Point of Approach

Another key principle is that of the closest point of approach (CPA). In a conflict the distance between aircraft will first decrease and then, if no collision occurs, increase again. The CPA is the location of the aircraft in space where, based on current state information, the two aircraft have the minimum amount of separation. If no action is taken, the location is always on the current flight path. Again, figure 2-6 can be referenced for an example scenario with a conflict area and displays the CPA as a red dot in the center. A yellow dashed line extends from the intruder to its CPA.

2-3-1 Relative Frame

In order to simplify the analysis and equations, we can use a relative frame that contains the following variables: $\boldsymbol{s} = \boldsymbol{s}_o - \boldsymbol{s}_i$, with ownship position $\boldsymbol{s}_o$ and intruder position $\boldsymbol{s}_i$, and

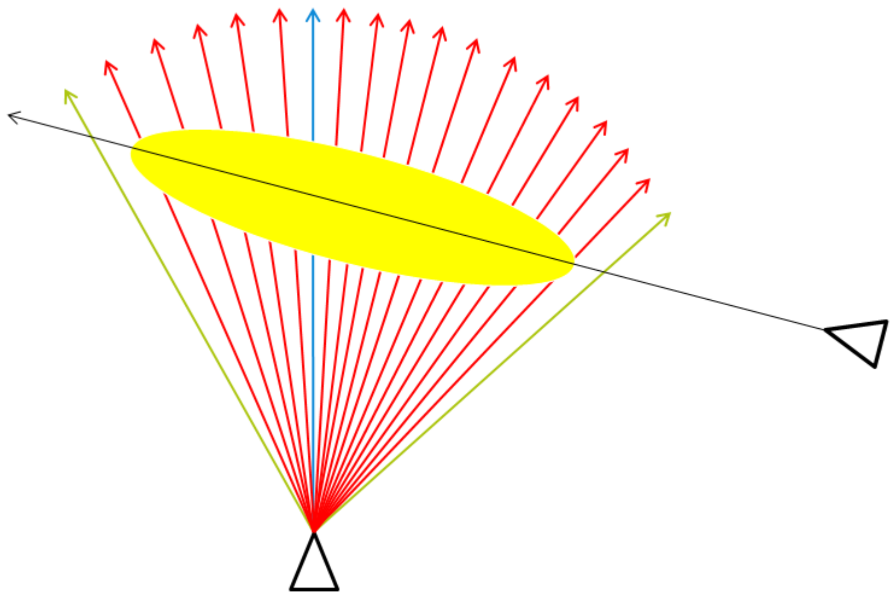

Figure 2-3: Conflict Area From Calculated Points and Vector Classification

the relative velocity vector $\boldsymbol{v} = \boldsymbol{v}_o - \boldsymbol{v}_i$, with ownship velocity $\boldsymbol{v}_o$ and intruder velocity $\boldsymbol{v}_i$. Implicit maneuver coordination also uses this relative coordinate frame. Intruder position is chosen to be at the origin. This frame is shown in figure 2-4 from which can be seen that the CPA in this frame lies on the line of $\boldsymbol{s} + \boldsymbol{v}t$ and is at the point of intersection of this line with an orthogonal line through the origin.

2-4 Implicit Maneuver Coordination

In previous research by NASA Langley [4, 8, 9], a framework has been defined for implicitly coordinating resolution maneuvers between aircraft that are in conflict or have lost separation. This framework is based on criteria that are proven to be conflict-free when one aircraft maneuvers and also, more importantly, when both aircraft maneuver. In the latter case, the maneuvers must be complementary to ensure the conflict is solved and not made worse. Any two algorithms satisfying the criteria are implicitly coordinated. Therefore, there is no longer a need for a specific algorithm to be mandated, as in the case of TCAS, allowing development of more efficient algorithms after a standard has been defined.

2-4-1 Criteria

Four criteria are defined for different situations, as shown in table 2-1. The criteria describe the conditions that horizontal and vertical maneuvers must meet in order to avoid loss of separation when in conflict or recover separation in case of loss of separation[1]. They are the

[1]Deficiencies were discovered in the loss of separation criteria that lead to formulation of new criteria based on the concept of repulsion instead of divergence. The new criteria are described in [21].

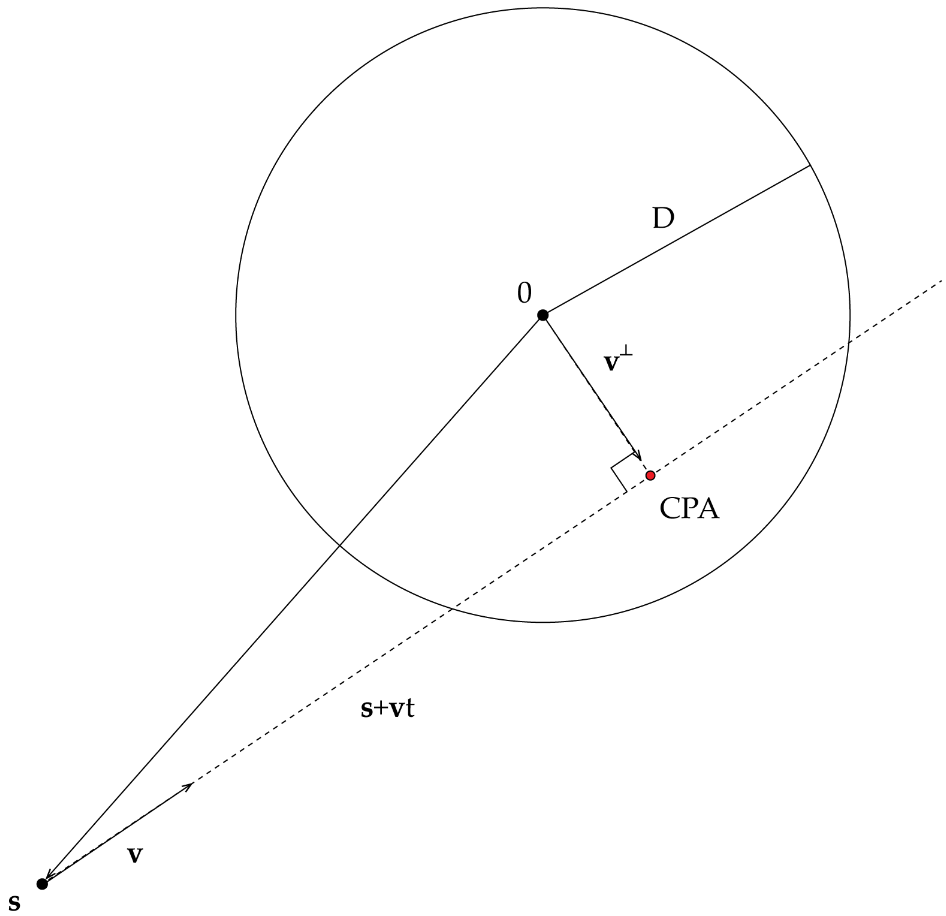

Figure 2-4: A Conflict In a Relative Coordinate Frame

result of a mathematical analysis and do not account for practical constraints, such as aircraft performance limitations.

2-4-2 Horizontal Criterion

The work in this thesis focuses on lateral maneuvers. The pilot making the maneuver decision likely has the most situational awareness of the horizontal conflict geometry, especially with multiple intruders, when using conflict probes on the navigation display. Also, vertical maneuvers are used for longer term separation by ATC and should remain available under normal circumstances for last-minute collision avoidance maneuvers by TCAS. Finally, preferring lateral maneuvers should make maneuvers more predictable. Additionally, in most cases of loss of separation, the time to a predicted collision is usually not enough for separation recovery maneuvers by the pilot, since TCAS will start to issue an alert. When a TA is issued, the pilot should take no evasive action and wait for an RA that will tell him to either climb or descend based on encounter geometry [22]. For these reasons, the criteria used is the

Table 2-1: Implicit Maneuver Coordination Criteria [8]

	In Conflict	In Loss of Separation
Horizontal	$(\boldsymbol{s} \cdot \boldsymbol{v'}) \geq \epsilon R(\boldsymbol{s} \cdot \boldsymbol{v'}^{\perp})$	$\boldsymbol{s} \cdot \boldsymbol{v'} > \boldsymbol{s} \cdot \boldsymbol{v}$ AND $\boldsymbol{s} \cdot \boldsymbol{v'} \geq \|\|s\|\|(D - \|\|S\|\|)/T_h$
Vertical	$\Delta > 0$ AND $t > 0$ AND $\delta = 1$ AND $s_z v_z \geq 0$ OR $\|s_z + tv_z\| \geq H$ AND $\delta(s_z + tv_z)v_z \leq 0$	$v'_z \neq 0$ AND $s_z v'_z \geq 0$ AND $s_z v_z \geq 0$ ==> if $v_z = 0$ then $break\_symm(s)(v'_z) > 0$ else $sign(v_z)v'_z \geq 0$

horizontal criterion for aircraft that are in conflict:

$$(\boldsymbol{s} \cdot \boldsymbol{v'}) \geq \epsilon R(\boldsymbol{s} \cdot \boldsymbol{v'}^{\perp}) \tag{2-1}$$

In this criterion we have the relative position $\boldsymbol{s}$ and relative velocity vector $\boldsymbol{v}$, as defined in section 2-3. The resolution vector is denoted by $\boldsymbol{v'}$. Furthermore, we have $R = \frac{\sqrt{s^2 - D^2}}{D}$ and ϵ, which will both be discussed further on.

2-4-3 Resolution Vector

To prevent loss of separation and thus solve the conflict, the distance between the aircraft at the CPA must be at least equal to the required separation. The minimum angle of the relative velocity vector that prevents loss of separation $\boldsymbol{v'}$, is then the relative velocity vector that is tangent to the protected volume. Shown in figure 2-5, the intruder is located at the origin, $\boldsymbol{s}$ is the position of ownship and thus endpoint of the relative position vector. As discussed before, at the CPA, there is a right perpendicular vector $\boldsymbol{v'}^{\perp}$ that lies on the line through the origin of the protected volume. R gives the proportion between the opposite and the adjacent side of the triangle formed by $\boldsymbol{s}$ and the extended vectors of $\boldsymbol{v'}$ and $\boldsymbol{v'}^{\perp}$, so the angle of $\boldsymbol{v'}$ can be found from $\boldsymbol{v'}^{\perp}$ using this factor. The dot product of the relative position with the right perpendicular relative velocity vector, multiplied with the factor R gives the minimum value of the dot product with the relative position vector, from which the tangent relative velocity vector can be determined. In other words, when the first part of equation 2-1 equals the second part, the vector $\boldsymbol{v'}$ denotes the relative velocity that leads the relative position on a line tangent to the protected volume.

2-4-4 Epsilon

As can also be seen in figure 2-5, there are two relative velocity vectors that are tangent to the protected volume. Epsilon in equation 2-1 is used to determine which tangent an aircraft should choose and it is the key to implicit maneuver coordination . Epsilon can be either +1 or -1, which translates to the left and right tangent from ownship point of view, respectively. This is all in a relative frame, whether ownship should make a turn to the left or the right from the current track therefore depends on the angle of the ownship velocity vector in relation to the tangent relative velocity vector. When one of the aircraft selects such a maneuver, the separation between the aircraft will go down to the minimum separation and then increase

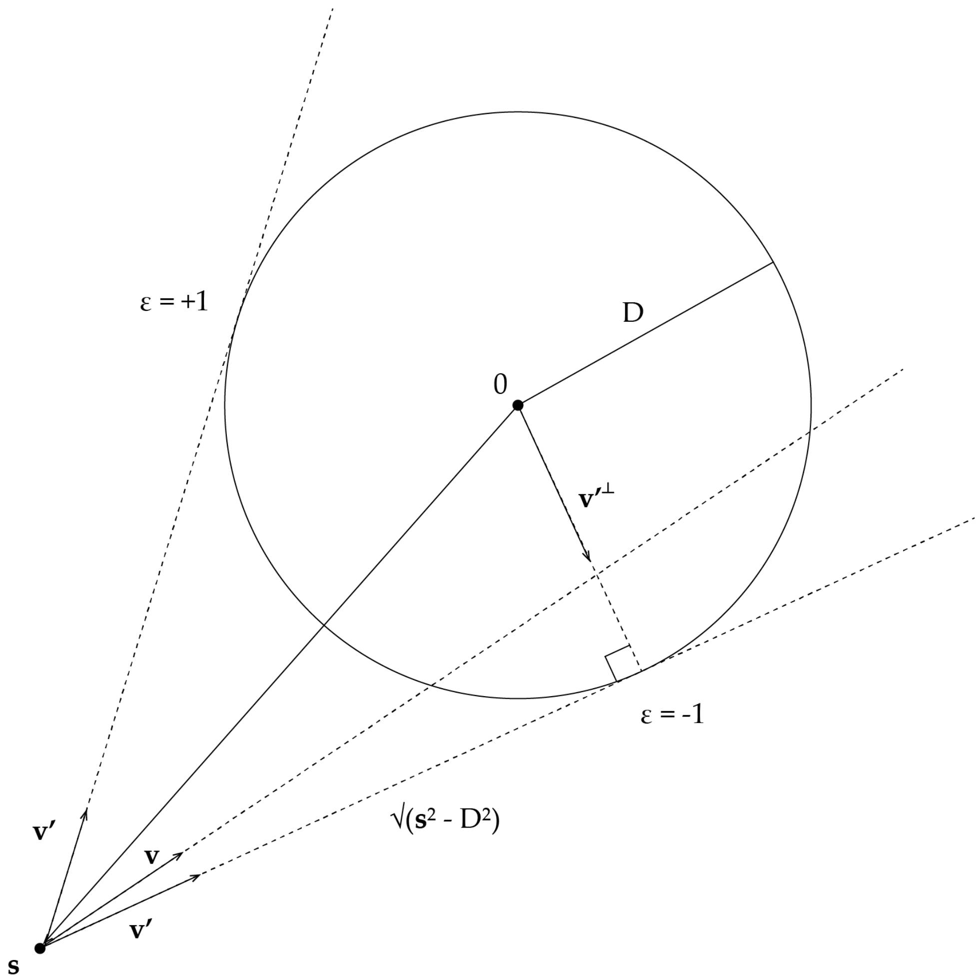

Figure 2-5: Epsilon Values and Tangent Velocity Vectors in a Conflict

again. To make maneuvers complementary when both aircraft maneuver, the aircraft must either both choose a left tangent or should both select a right tangent, from their point of view. So as long as the value for epsilon used in the calculations is the same for both aircraft involved in the conflict, the resulting calculated maneuvers will be implicitly coordinated. Thus, there is a need for a universal policy on what definition of epsilon is to be used in the algorithms so any two algorithms are implicitly coordinated.

2-4-5 Epsilon Policies

There are three main policies for epsilon to be considered [9]:

- $\epsilon = +1$
- $\epsilon = -1$

- $\epsilon = (\boldsymbol{s} \cdot \boldsymbol{v}^{\perp}) \geq 0$

Choosing either +1 or -1 as a policy means both aircraft should always choose either a tangent to the left side or to the right side of the protected zone, respectively. Figure 2-6 shows a scenario in the simulator from which the disadvantages of choosing such a policy can be found. Ownship is shown as the white triangle, the intruder in cyan. The conflict area lies between the aircraft, showing the area where separation will be lost if ownship enters this space. If the policy for epsilon is chosen to be +1, the aircraft in this conflict scenario need to make a large deviation from their flight path in order to make a turn to the left around the conflict area. Additionally, the extended maneuver takes the aircraft's track through the closest point of approach in the conflict, increasing the chance of going below the minimum required separation.

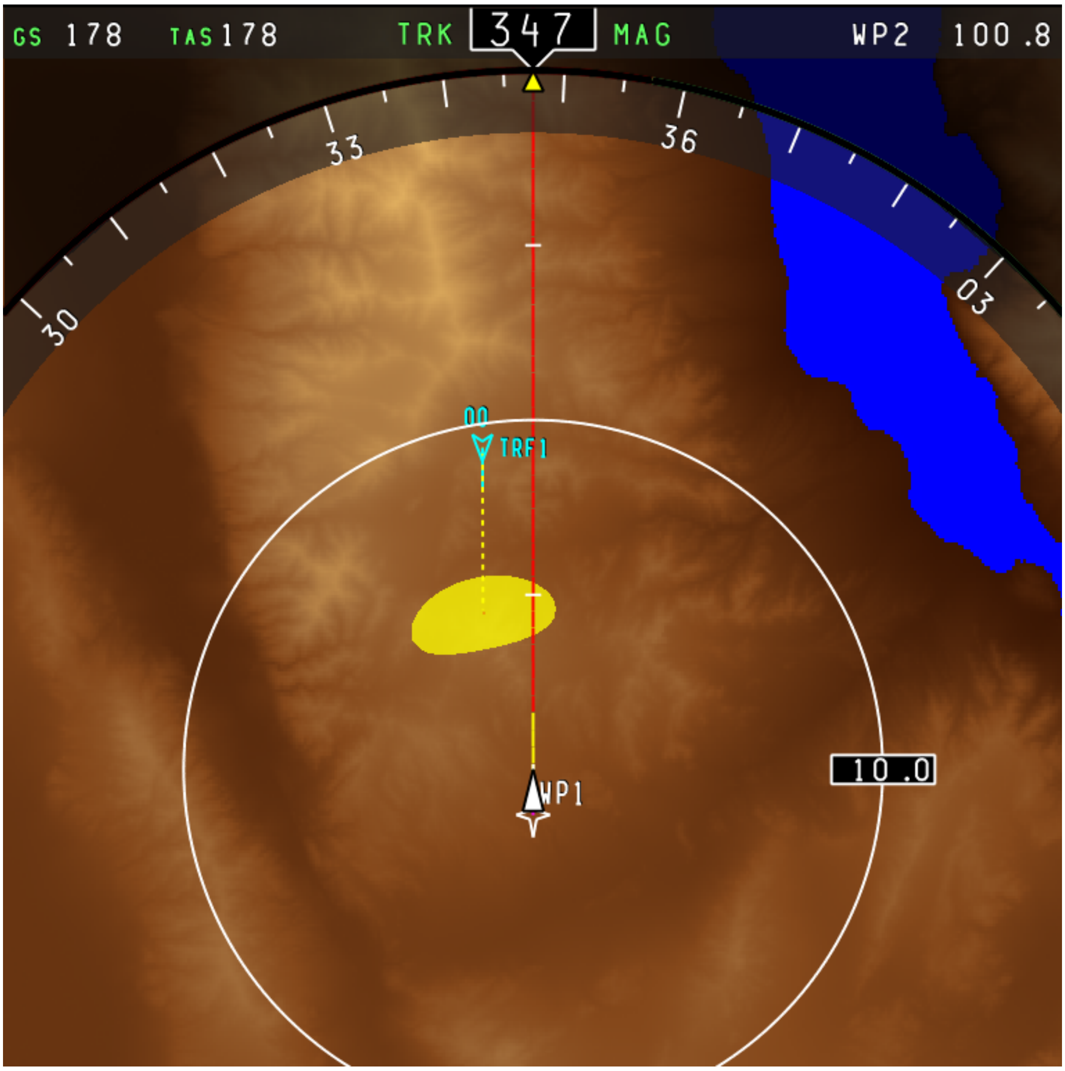

Figure 2-6: Scenario Showing Disadvantages of Epsilon +1 Policy

2-4-6 Dot Product Policy

The third policy for epsilon is based on the dot product and uses state information to calculate the relative position $\boldsymbol{s}$ and relative velocity $\boldsymbol{v}$ vectors, using the same definition as in section 2-3. Then taking the dot product of the relative position and the right perpendicular vector of the relative velocity. Epsilon takes on the opposite sign of the result. The value of epsilon must be the same for both aircraft. From the definition of the relative position and relative velocity it can be seen that:

$$(\boldsymbol{s}, \boldsymbol{v})_{ownship} = (-\boldsymbol{s}, -\boldsymbol{v})_{intruder}$$

Clearly, both aircraft will determine the same value for epsilon from the dot product using these vectors. The dot product policy is preferred over the other policies, since it always chooses the smaller maneuver that immediately increases minimum separation of the approach, moving the flight path away from the CPA.

2-4-7 Strengths

The strength of a system using implicit coordination is that pilots can theoretically solve a large variation of conflict scenarios by using the advice provided by a conflict detection and resolution (CD&R) algorithm combined with an implicit maneuver coordination policy. The algorithm outputs the maneuver options the pilot has or which areas the pilot should avoid. Areas on the track band, vertical speed band and ground speed band can be shown in either red when an area should be avoided or green when the area is safe or when a maneuver in that direction should be made[2]. Figure 2-7 shows an implementation of implicit maneuver coordination on a navigation display. The CPA is at the end of the dashed line originating from the intruder. It is in the center of the small red dot that marks the collision hazard area. In this conflict scenario, ownship should make a turn to the right, with a heading that is shown in green in the heading band. As can be seen, the minimum angle that solves the conflict, is the heading that forms a tangent line from ownship to the conflict area. This system allows a pilot to make corrections and avoid loss of separation without even having to know where the surrounding aircraft are. Also, conflicts can be resolved by either aircraft involved, when only one moves or when both maneuver according to the same coordination policy.

2-5 Conflict Probing and Implicit Maneuver Coordination

Conflict probing is a CD&R algorithm that can support pilots in obtaining a higher level of situational awareness [11]. It provides information about the future state of ownship in terms of separation with surrounding aircraft and thus can be considered to contribute to a level 3 situational awareness [24]. Using conflict probing for implicit maneuver coordination therefore has the advantages that pilots can see exactly how the offered resolutions will resolve

[2]Track angle, ground speed, and vertical speed prevention bands algorithms and formal verifications are presented in [23].

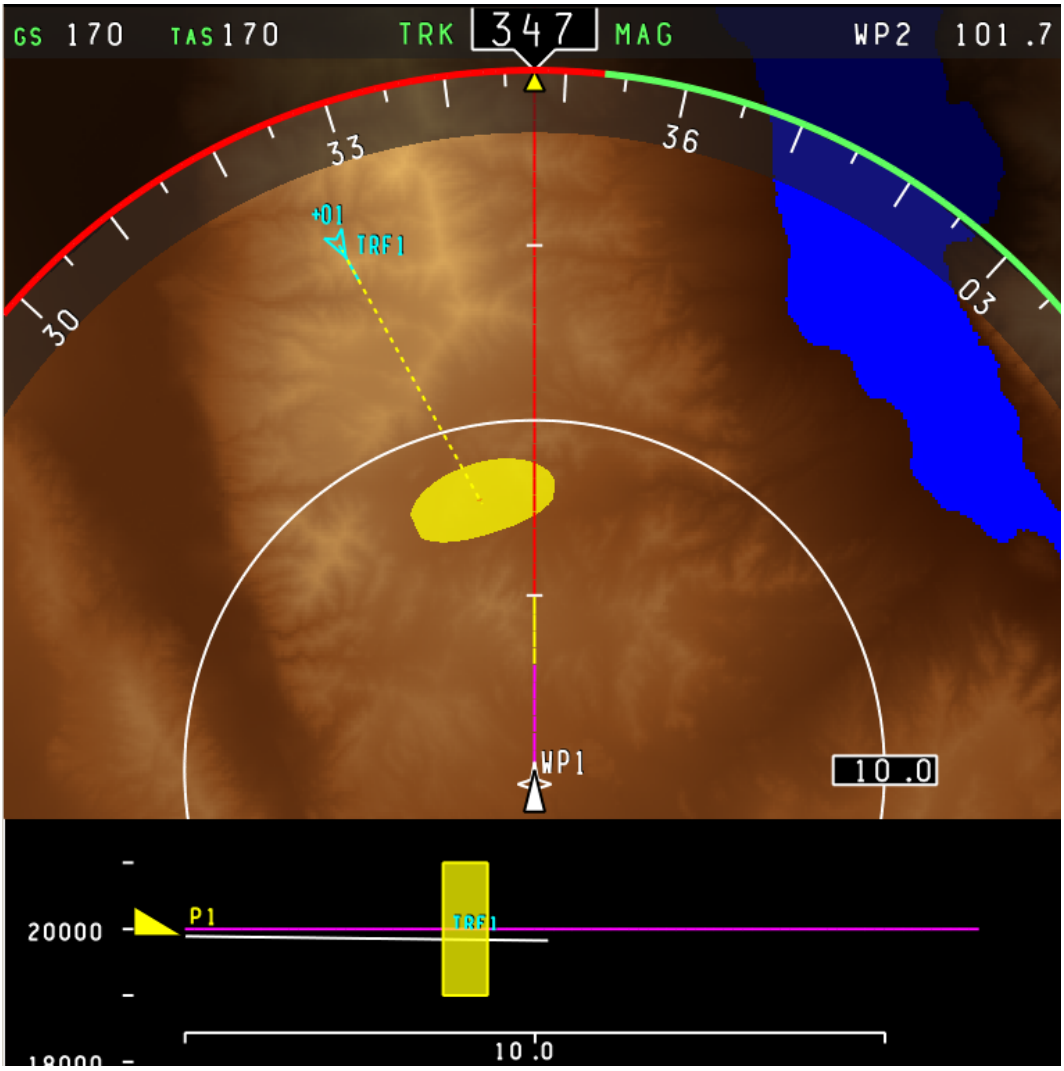

Figure 2-7: Implicit Maneuver Coordination Advice in Heading Band

the conflicts and gives them the ability to do verification, which will lead to an increased acceptance of the resolution maneuvers. It also takes away much of the cognitive workload of the pilot that would be otherwise needed to mentally extrapolate the intruder position and then determine the best possible maneuver.

2-5-1 Tangential Resolutions Satisfy Horizontal Criterion

Before an algorithm can be used for implicit maneuver coordination, it must be proven to satisfy the criteria. Tangential solutions are shown to satisfy the horizontal criterion in [10]. If we use conflict probing and select a maneuver that leads ownship on a path tangent to the conflict area, this means a relative velocity vector is chosen that leads the relative position on a trajectory tangent to the protected zone around the intruder and thus forms a tangential resolution as defined in [10]. This is not a formal proof, but enough to support the use of conflict probing for implicit maneuver coordination in this thesis.

2-5-2 Dot Product Policy and CPA

The dot product policy will be used to coordinate the value of epsilon. With this policy, the resulting maneuver always moves the flight path away from the location of the intruder at the closest point of approach, which is located on the current flight path of the intruder. This can be understood by considering three different scenarios. In case of a predicted collision, the two CPAs will occupy the same point in space, the point where the collision will occur if no action is taken. Such a scenario is shown in figure 2-8.[3] The black arrows in front of the aircraft represent their velocity vectors, with ownship on the left. The dashed lines represent the aircraft's flight paths and the CPA is shown as the red dot at the intersection of the flight paths. The relative position and right perpendicular velocity vectors are also shown. The value of epsilon is found from the dot product of these two vectors. Here the dot product is zero, so epsilon has the value of -1 and the implicit maneuver coordination advice to both is to choose the right tangent, which moves both aircraft away from the CPA of the intruder from their perspective. In this case, a left tangent would have the same result, the conflict is solved as long as both aircraft use the same direction.

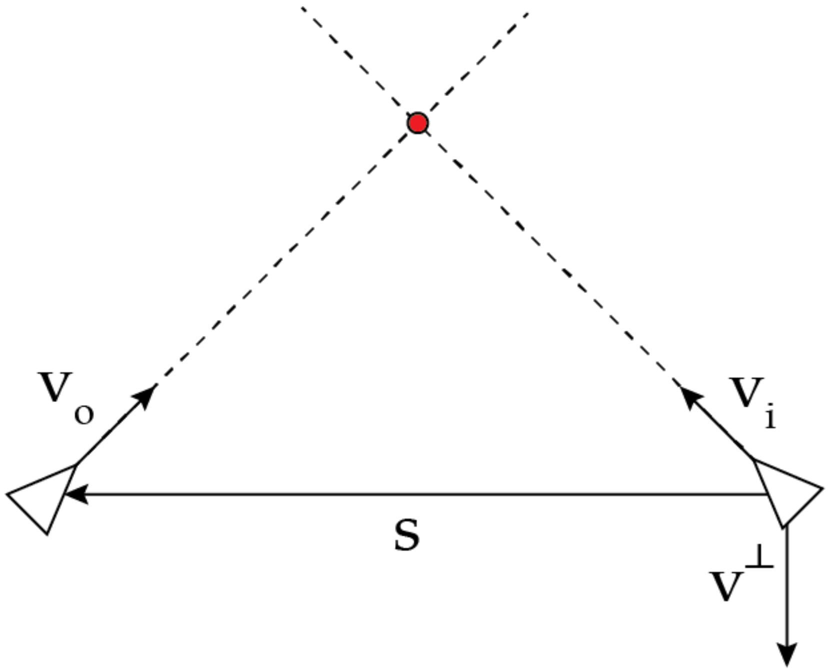

Figure 2-8: Two Aircraft On a Collision Course Resulting In a Right Tangent Advice

In the next scenario in figure 2-9, ownship flight path is moved to the left. The location of the aircraft at the CPA is no longer in the same point, there are now two red dots on the respective flight paths and a collision is no longer expected. Clearly, changing the angle of ownship velocity vector counterclockwise has the same effect on the relative velocity vector. This makes the dot product return a value smaller than zero, with an epsilon of +1, both

[3] Although figures 2-8, 2-9 and 2-10 are drawn based on simulations in MATLAB, they are only added for illustrative purposes and are not supposed to be exact.

aircraft are now advised to choose a left tangent. Maneuvering to the left moves both aircraft in the direction opposite to the location of the intruder at the CPA.

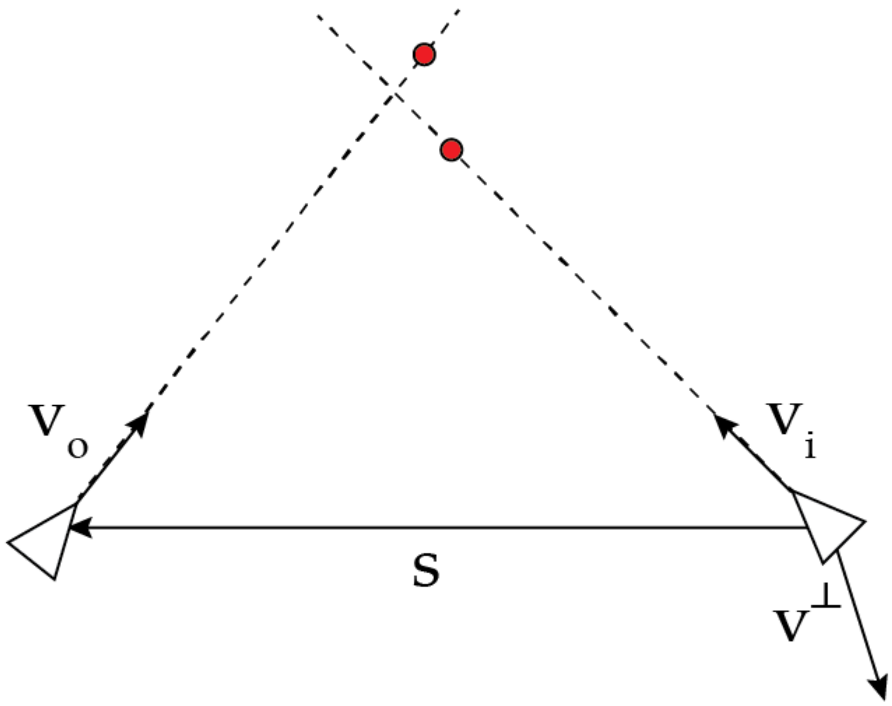

Figure 2-9: Two Aircraft In Conflict Resulting In a Left Tangent Advice

The final scenario in figure 2-10 has ownship flight path moved to the right. Again the location of the aircraft at the CPA is at different points in space. With the new relative velocity vector, the dot product is larger than zero, so epsilon is -1 and the advice is to choose a right tangent. Again, this moves the aircraft away from the location of the intruder at the CPA.

The same effects of moving the CPAs apart and changing the direction of the implicit maneuver advice are obtained for increasing or decreasing the speed of one of the aircraft.

2-6 Assumptions

The following assumptions are made for the remainder of this thesis:

- State information is always accurate[4] and complete.
- Aircraft are in straight flight at constant speed and with a speed ratio with other aircraft close to one leading up to, during and after a predicted conflict, unless otherwise stated.

[4] Accurate meaning within 95% accuracy defined by ADS-B messages containing measurements of horizontal position and velocity accuracies as Navigation Accuracy Category, NACp and NACv. Accuracy intervals can be used in calculation of the outline of conflict areas by conflict probes as described in [25].

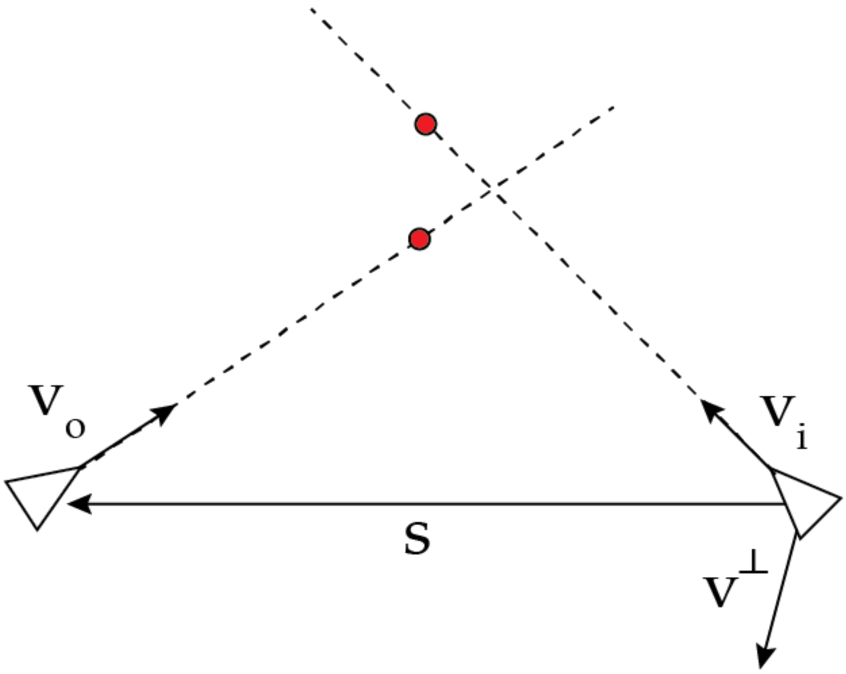

Figure 2-10: Two Aircraft In Conflict Resulting In a Right Tangent Advice

- Aircraft dynamics are neglected; turns are made instantaneously.

2-7 Conclusion

Maneuvers performed by pilots for self-separation are preferred to be lateral. These maneuvers can be implicitly coordinated between aircraft based on a horizontal criterion that contains the requirements for the minimum angle of the velocity vector ownship should choose to prevent loss of separation. The criterion also contains a coordination variable ϵ that determines the maneuver direction and ensures different algorithms are implicitly coordinated. The dot product policy for ϵ that bases the maneuver direction on the dot product of the relative position and velocity is preferred since it results in minimal and safe maneuvers.

Since tangential resolution algorithms were shown to satisfy the horizontal criterion in [10], conflict areas resulting from conflict probes can be used to find the minimum lateral maneuver used for implicit maneuver coordination. The maneuver direction given by the dot product policy can also be obtained from the location of the closest point of approach relative to ownship flight path.

Chapter 3

Special Cases

Not every possible conflict between two aircraft can be adequately resolved through implicit maneuver coordination using the key principles from chapter 2. Addressing the first research question from section 1-4, there are two types of special cases that require a specific solution. The first is the symmetrical conflict discussed in section 3-1 and the second the low speed ratio conflict in section 3-2. Both cases will be analyzed and given a possible solution.

3-1 Symmetrical Conflicts

The first special case is the symmetrical conflict scenario of which an example is shown in figure 3-1. In this scenario the aircraft approach each other either head-on or at an angle with a close to equal ratio between distance to CPA and speed:

$$\frac{(\text{Distance to CPA})_o}{\boldsymbol{v}_o} \approx \frac{(\text{Distance to CPA})_i}{\boldsymbol{v}_i} \tag{3-1}$$

Figure 2-8 is also an example of a symmetrical scenario. In these scenarios the aircraft are expected to collide when no action is taken and the CPA for both aircraft will be at the same location. Furthermore, the dot product will be zero for both of the aircraft, thus both should make a turn to the right and the conflict is solved.

3-1-1 Case Description

The problem is that in reality, the aircraft will never approach exactly on a collision course, but their track angle and speed will be fluctuating. Therefore the dot product can fluctuate between zero or a small positive value and a small negative value. Whenever this happens, the advice shown to the pilot will also fluctuate between making a right or left turn, which can result in a very dangerous livelock. Ownship track in figure 3-1 is slighty to the left of that of the intruder, which is why the implicit maneuver coordination advice is to make a

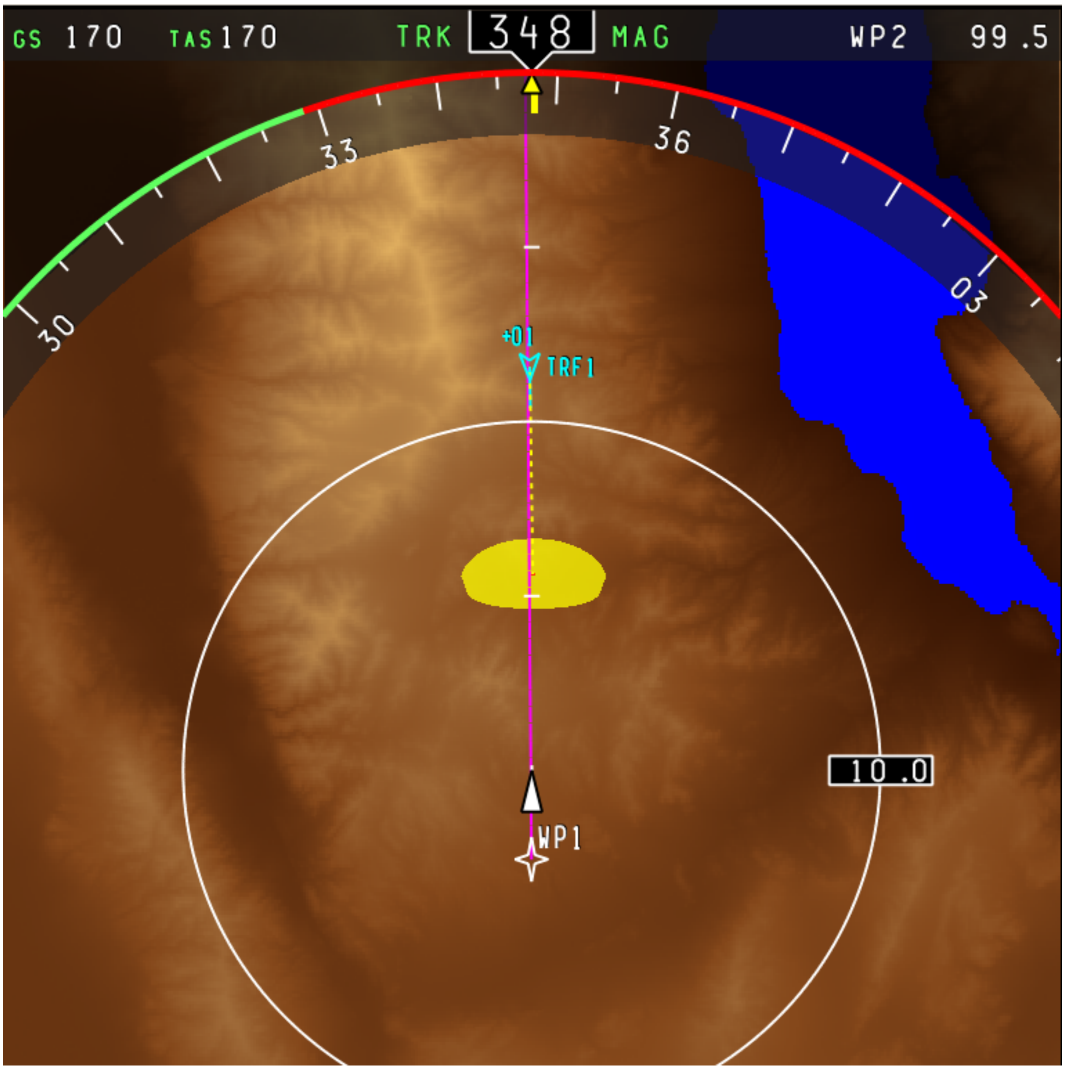

Figure 3-1: Symmetrical Conflict Scenario

left turn. If the intruder has already started a maneuver based on the past geometry where ownship heading was to the right of the intruder, both aircraft could now be making a turn to the same side. As soon as one aircraft notices this, it would start to correct by turning in the other direction. Before this becomes apparent to the other aircraft, it could also have made the same decision, resulting in again both turning toward each other. And so on.

3-1-2 Possible Solution

In TCAS, which only provides vertical resolution advisories, a similar situation exists when both aircraft approach in the same horizontal plane. TCAS uses a communication protocol to uniquely determine the maneuver each aircraft should follow to break the symmetry [26]. NASA is performing research on how to solve this situation when using implicit maneuver coordination. This thesis will not explore this topic further, however, three possible methods are proposed, though not discussed in detail, in [21]:

- Use dead bands: freezing the resolution maneuver while in a symmetrical conflict.
- Filter the direction: freezing the maneuver direction.
- Use future resolutions: computing a future resolution and holding it while it is valid.

3-2 Low Speed Ratio Conflicts

The second type of scenario that requires special attention is when the aircraft in a conflict are approaching each other at different speeds. Specifically, potential conflict resolution problems arise when ownship is flying at a significantly lower speed than the intruder. Using the following definition for speed ratio:

$$\text{Speed Ratio} : \frac{\boldsymbol{v}_o}{\boldsymbol{v}_i} \tag{3-2}$$

these scenarios are referred to as low speed ratio conflicts. In most cases two aircraft that are involved in a conflict, especially commercial airliners, will fly at a similar speed and will have a speed ratio close to one. However, there are cases where one aircraft has a significantly lower speed, resulting in a speed ratio significantly less than one. This could be the case for example when UAVs, once integrated into the National Airspace System, are approached by a commercial airliner.

3-2-1 Case Description

In terms of a conflict, the relevant variables are the relative position and the relative velocity of both aircraft. These two variables are also the key in solving a conflict. Maintaining a certain value of minimum separation means the length of the relative position vector should not go below this value, figure 2-5 can be used as a visual reference. If we set the coordinates of the intruder to the origin in the horizontal plane, then the length of the relative position vector is determined by the distance to the origin of the location of ownship. Also, the relative velocity determines the speed and direction of the point representing ownship in the same plane. In order to stay out of the protected zone, which can be seen as a circle around the origin with radius D, the relative velocity needs to have at least an angle that will lead the relative position on a line tangent to the protection zone. The lower the speed ratio, the smaller the resolution space becomes for that aircraft, in terms of achievable angles for the relative velocity.

Simulations in MATLAB were done to illustrate the effect for different speed ratios, resulting in the figures 3-2 and 3-3. In the simulations, an intruder is approaching ownship from a 20 degree angle to north. The relative frame introduced in section 2-3 is used, the graphs show relative velocity vectors or resolution vector space for the speed ratios of 1.0 and 0.3, respectively. Each vector in the graphs represents a 10 degree change in angle of ownship velocity, from which the relative velocity vector is calculated, with constant intruder velocity. These 36 vectors cover the range of directions that the relative velocity can reach by changing the ownship velocity angle.

From figure 3-2, with a speed ratio of 1.0, it can be noted that the closer ownship velocity angle comes to the angle of the velocity of the intruder, the smaller the relative velocity becomes to the point of the two vectors canceling out. This means their relative position is increasingly slower diverging until it remains constant when they are flying in the same direction. Also, changes to ownship angle can point the relative velocity to almost every angle. Since the intruder is approaching from a 20 degree angle, the protected volume can be imagined to be in the top right corner of the graph. Clearly, with a 1.0 speed ratio there are enough options available for ownship to solve the conflict.

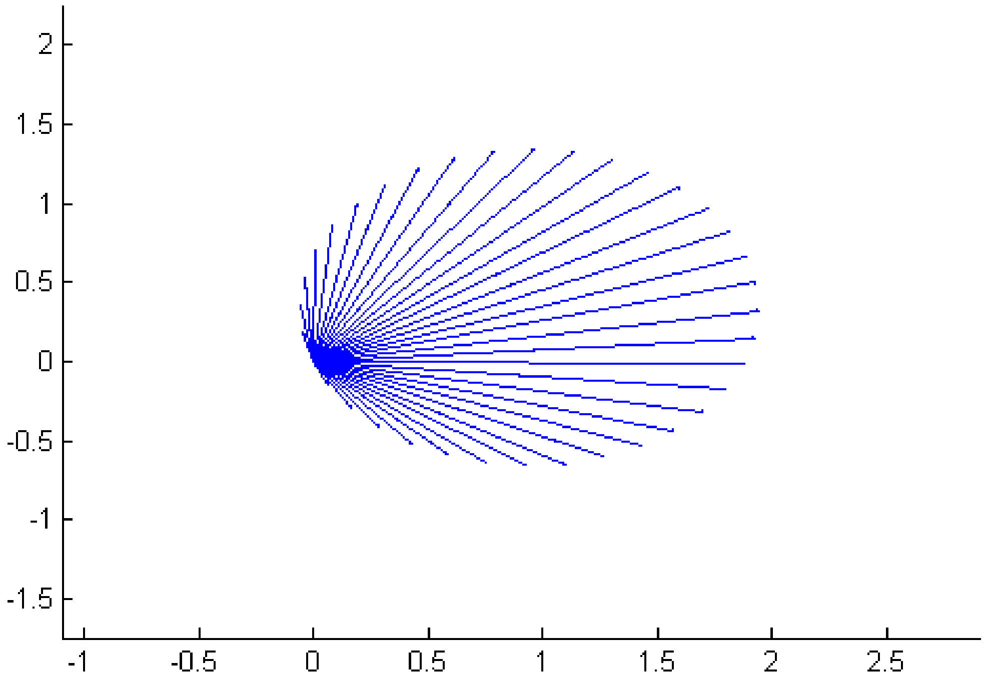

Figure 3-2: MATLAB Simulation of Resolution Vector Space For a Speed Ratio of 1.0

Figure 3-3 on the other hand shows a different picture. It is generated in the same way as figure 3-2, but for ownship speed that is only 0.3 times the speed of the intruder. The resolution vector space has become drastically smaller, changes in ownship heading still have an effect on the relative velocity, but the resulting angle range is now very limited. Again imagining the protected volume in the top right corner it becomes clear that, especially with a small distance to conflict, ownship will not be able to avoid loss of separation with a lateral maneuver since all relative velocity vectors are pointing in that direction. Also, not all angles displayed in the figures will be available in flight, depending on ownship turn speed which can be a limiting factor.

The same effect is seen in the simulator, as shown in figure 3-4 and 3-5. Again speed ratios are used of 1.0 and 0.3, respectively. The figures show a scenario similar to the one used in MATLAB. The situation in figure 3-4 with a speed ratio of 1.0 is again not a real problem. The intruder will simply pass behind ownship, loss of separation will not occur.

With a speed ratio of 0.3 as in figure 3-5, however, the same scenario now no longer offers a lateral solution. This can be seen by the conflict area wrapping around ownship and

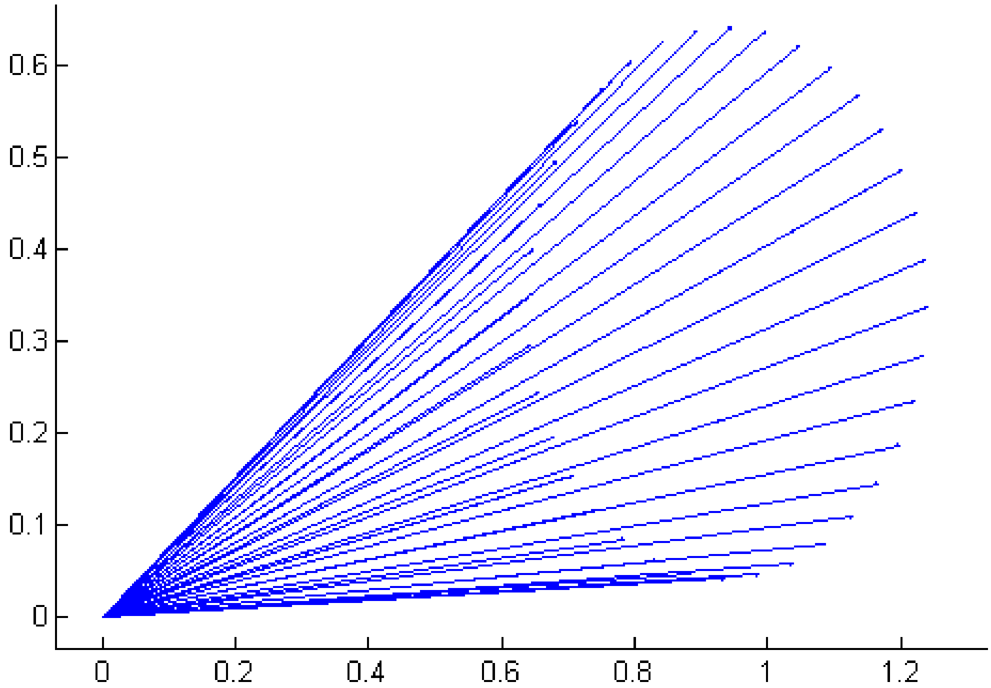

Figure 3-3: MATLAB Simulation of Resolution Vector Space For a Speed Ratio of 0.3

by the heading band shown entirely in red.

3-2-2 Possible Solution

As the speed ratio decreases, the resolution space becomes smaller and the conflict is more likely to become insolvable by ownship since changes in its velocity vector will only have a small effect on the relative velocity. On the other hand, the maneuver needed by the faster travelling aircraft becomes smaller as the ratio decreases. Since the UAV will not be capable to increase its speed to increase the resolution space, this type of conflict can only be solved by a maneuver of the faster travelling aircraft, by a vertical maneuver of the UAV or a lateral maneuver by the UAV when it is able to make a maneuver ahead in time. In other words, the pilot or UAV operator needs to know at what temporal or spatial distance to conflict his lateral resolution options will no longer be available.

Figures 3-2 and 3-3 show that the intruder track angle has an increasing effect on the angle of the relative velocity as the speed ratio decreases. This means the resolution space is not just influenced by the speed ratio, but also by the intruder track angle. The temporal or spatial distance at which lateral maneuvers no longer prevent a conflict therefore depends on speed ratio, the angle at which the intruder flight path intersects ownship flight path in the horizontal plane and maximum bank angle of ownship. As ownship approaches the conflict, the minimum angle of the ownship velocity vector needed to prevent loss of separation will increase. The time to conflict at which lateral options are no longer available is therefore determined by the moment in time the minimum resolution angle for ownship equals the

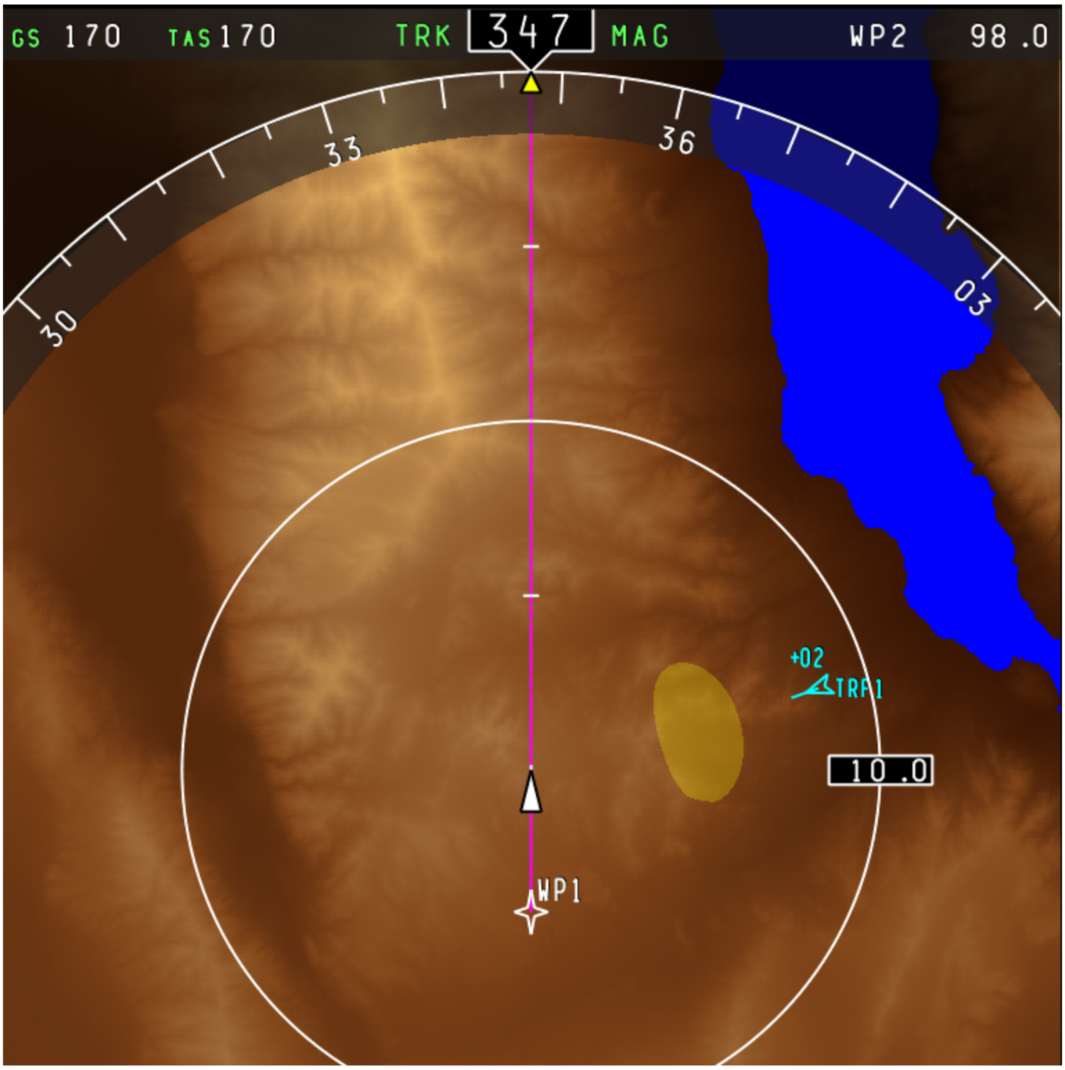

Figure 3-4: Conflict Area for a Speed Ratio of 1.0

maximum bank angle. The separation between the aircraft at this moment in time represents the distance to conflict at which lateral maneuvering resolution options become unavailable.

To chart the effect of combinations of speed ratio and intruder track angle on time and distance to conflict, approach scenarios were simulated in MATLAB. The scenarios are defined by a common intruder CPA that lies 0.2 NM to the left of ownship flight path, with an ANSD of 5 NM. The simulations start at 60 minutes to CPA. Every second the dot product is recalculated. Although the CPA is always on the left side, the dot product rule can still lead to left turn advises at lower speed ratios and symmetrical scenarios. The 0.2 NM margin ensures a right turn advise in the latter case that is affected by small changes in the angle of the relative position. During the simulations there are no maneuvers or speed changes. The starting position for both aircraft is determined from the CPA, based on speed and intruder track angle, at a set time to CPA. Ownship flies a 0 degree track.

At every time instance, the GO track algorithm [27] is used to calculate the minimum

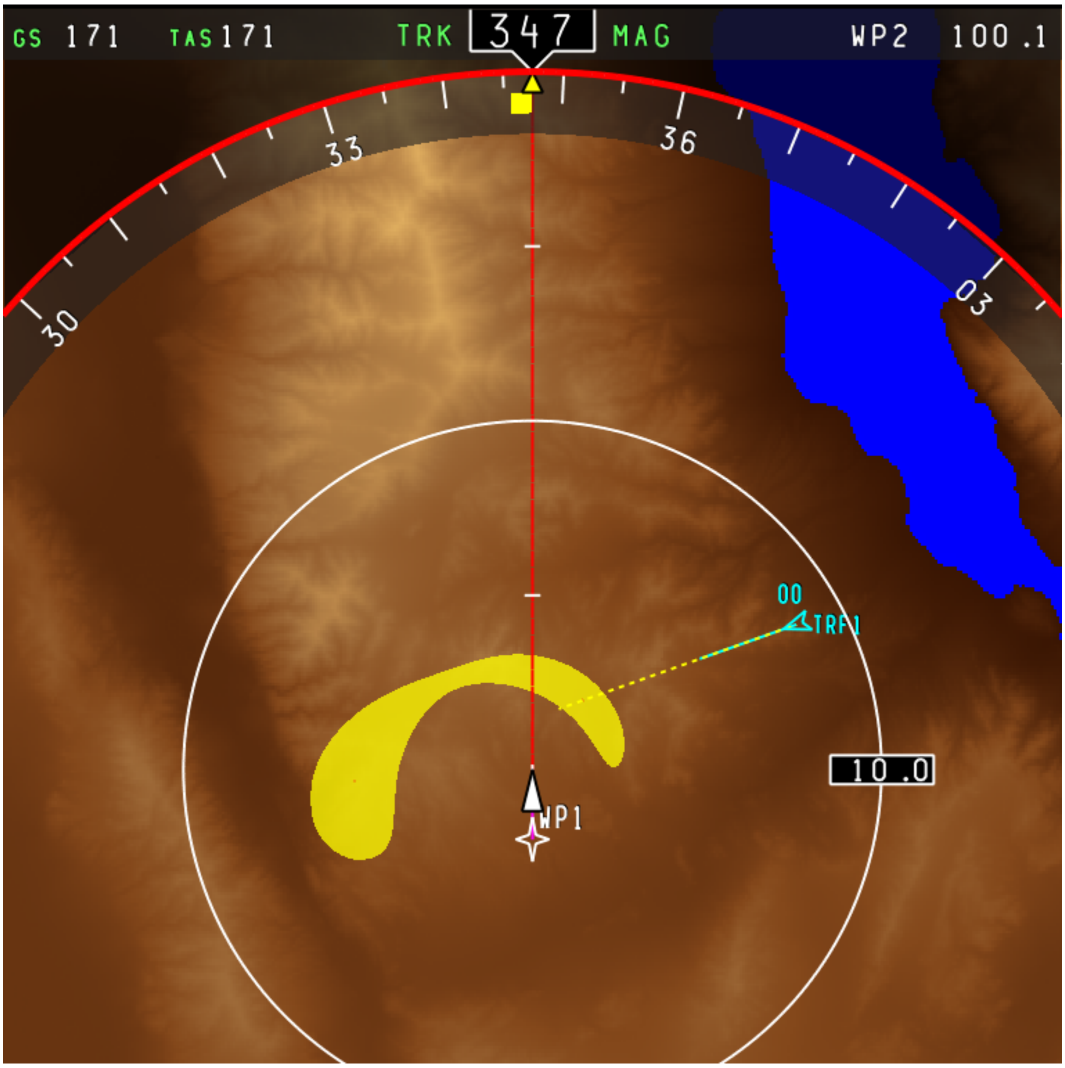

Figure 3-5: Conflict Area for a Speed Ratio of 0.3

velocity vector for ownship that prevents loss of separation. The maximum bank angle used is 30 degrees, a commonly used value for UAVs and an appropriate value for other aircraft limiting flight path deviation. Figure 3-6 shows the time at which the lateral maneuver options are no longer available for different speed ratios and a selection of intruder angles, figure 3-7 shows the distance to conflict at these time instances. The results can roughly be divided into two groups: intruder track angles between 90 and 270 degrees (oncoming traffic), and track angles between 270 and 90 degrees (overtaking traffic). The results in the first group share a very similar and expected shape. At low speed ratios the lateral maneuver must be performed at a large time to conflict, this time decreases as the speed ratio increases, also, the results are converging toward the higher speed ratios. The second group generally follows a similar base curve, however, this group also contains peaks for different ranges of speed ratios. This is true for all intruder track angles within the two groups.

The peaks in figures 3-6 and 3-7 provide important insight. For an intruder track angle of 350 degrees, the peak occurs at speed ratios between 0.8 and 1.1. The intruder approaching from the right at a track close to parallel to ownship's results in a long outstretched conflict area just to the right of ownship flight path. Making a right turn around this area must be done before this area starts to prevent a turn within 30 degrees to the right of ownship. This is true for high speed ratios down to a ratio of 1.0. At a speed ratio of 0.9 and below, the dot product rule will return a left turn advice, although the CPA is still at the same location in the non-relative frame. This occurs for all combinations of speed ratio and intruder track angle shown in table 3-1 and for any lateral offset of the CPA from ownship flight path. The closer intruder flight path is to being parallel to ownship flight path and the lower the speed ratio, the more likely the maneuver advice is in the direction toward the CPA. For the given combinations, the simulator will show a conflict area similar to the one shown in figure 3-5 that, upon close inspection, contains two CPAs, one on either side of ownship. Along the intruder flight path, there are two points where a collision would occur if ownship were to intersect it. In these cases, the advice to make a maneuver in the direction opposite of the CPA becomes ambiguous; the dot product rule can be used to determine the maneuver direction instead. The peak between 0.8 and 1.1 is a result of the conflict area closing in to the right, increasing the time to conflict at which a maneuver must be made, then returning to the average values seen for other intruder track angles after the maneuver direction has changed.

By placing the CPA on the left side, ownship is in most configurations forced to make a turn to the right. For an intruder overtaking ownship at a track angle of 50 degrees, the result is the extreme peak shown in the corresponding curves in figures 3-6 and 3-7. The effect seen for an intruder track angle of 350 degrees is seen as well for an angle of 50 degrees, although with different magnitude and at different speed ratios. For this angle, the maneuver direction is changed at a speed ratio of 0.6 and below. At a speed ratio of 0.7, the conflict scenario is unsolvable by ownship, shown by the time to conflict being at 60 min, the duration of the simulation. The necessary velocity vector angle to prevent conflict is outside of the resolution vector space of ownship. These cases can be found by using the following equation from the GO-track algorithm [27]:

$$||\frac{||\boldsymbol{v_i}||}{||\boldsymbol{v_o}||} \times \sin(\beta - \text{track}(\boldsymbol{v_i}))|| > 1 \tag{3-3}$$

with β the track angle of the relative velocity resolution vector. The first part of the equation describes the minimum multiplication factor that must be applied to the ownship velocity vector in order to achieve the minimum angle for the relative velocity resolution vector. If this factor is larger than 1, there is no lateral maneuver available to ownship that will lead to at least the minimum angle for the relative velocity to maintain separation. An increase in speed lowers the factor and could provide a resolution option. Another solution is possible. At a 0.7 speed ratio, epsilon equals -1, β is the resolution vector based on the tangent in the direction dictated by epsilon. Simulating the same approach using a forced value for epsilon of +1, with the new value for β the factor in equation 3-3 is no longer larger than zero. The time to conflict is then 8 minutes, much more in-line with the results from other intruder angles.

For an intruder track of 300 degrees there are no solutions at speed ratios of 0.5 and below. The inverted maneuver direction at 0.4 and below does not lead to solutions either in this case, since the intruder is here on a track in the same direction. However, if we reverse the current maneuver direction for all cases of 0.5 and below, we do get a valid result. Finally, at an intruder track of 100 degrees the maneuver direction does not change, the time to conflict is rapidly increasing toward the lower speed ratios due to the intruder being on a track close to perpendicular to ownship track.

The results of these simulations for every 10 degrees in the entire range of intruder track angles are shown in figures 3-8 and 3-9. These are all variations of the cases discussed for the previous selection of intruder track angles. Here the separation into two groups becomes even more apparent. Figures 3-10 and 3-11 show the same simulations for an ANSD of 3 NM. This reduction of the ANSD of 40 percent also results in a decrease in the distance to conflict of around 40 percent.

The reference speed, the speed corresponding to a speed ratio of 1, in the simulations is 850 km/h, a typical commercial airline cruise speed. If, for instance, the reference speed is halved, the time to conflict doubles and the distance to conflict measure is halved. Time to conflict and distance to conflict can be used interchangeably since neither is more consistent across speed ratios or intruder angles.

For some approach scenarios lateral maneuvers are only possible if the opposite direction is chosen to that of the dot product rule. As the aircraft pass a temporal / spatial threshold, the aircraft will enter a critical time / separation window in which all maneuvers must adhere to the maneuver direction that follows from the chosen epsilon policy. Outside of this window, maneuvers do not need to be coordinated, since it is unlikely that both the aircraft involved in the conflict will maneuver at the same point in time. Also, if they do, it will not immediately lead to a loss of separation or collision hazard.

All data points in figures 3-6, 3-7, 3-8 and 3-9 follow from the time instant or distance to conflict at which the 30 degree resolution space for ownship is no longer available. Taking for example an intruder track angle of 200 degrees, figure 3-12 shows how the resolution space decreases with time. For most speed ratios, there is a small gradient to the loss of resolution space until a few minutes to conflict. The gradient then quickly becomes much larger and most of the resolution space is lost in the final minutes. The smaller the gradient, the easier it is for the pilot to predict how the conflict will progress and the effects on the resolution space. The critical time window should contain the following:

1. The time to conflict at which the resolution space is lost (figure 3-8).
2. The final stage in the loss of resolution space that is marked by the gradient of the loss of resolution space becoming larger than a threshold (figure 3-12). This threshold should be quantified in future research based on aircraft performance and pilot perception and situational awareness.
3. Pilot response delay and decision time.
4. Additional safety margins.

The lateral resolution options are no longer available to the pilot or operator at the moment shown in figure 3-8 for the given parameters or in specific cases at the start of the critical time window. These are the minimum values that should be used for the look-ahead time, in either worst-case or determined for each scenario.

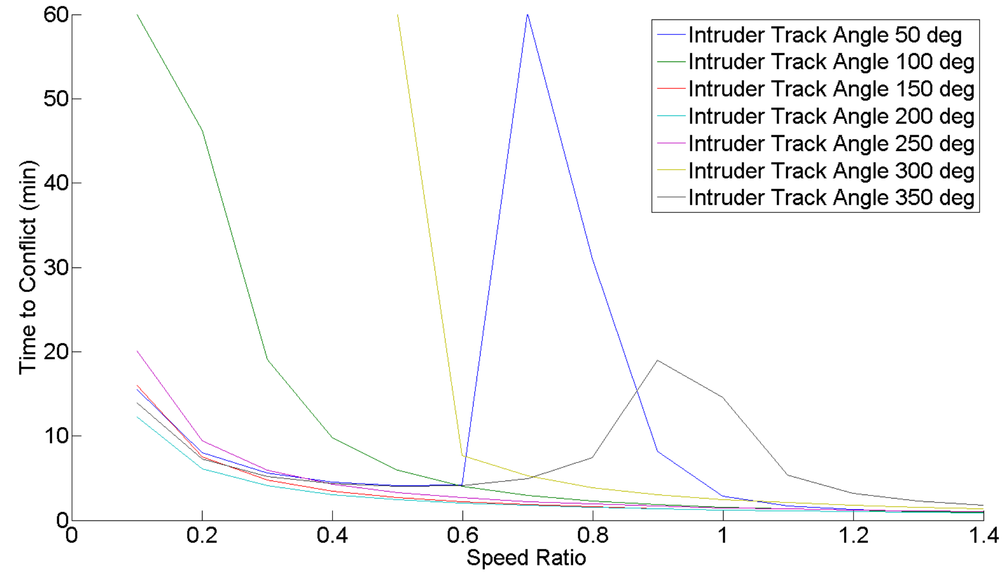

Figure 3-6: Loss of Lateral Resolution Space (30 degrees) at Time to Conflict for 5 NM ANSD and 850 km/h Reference Speed (Selection)

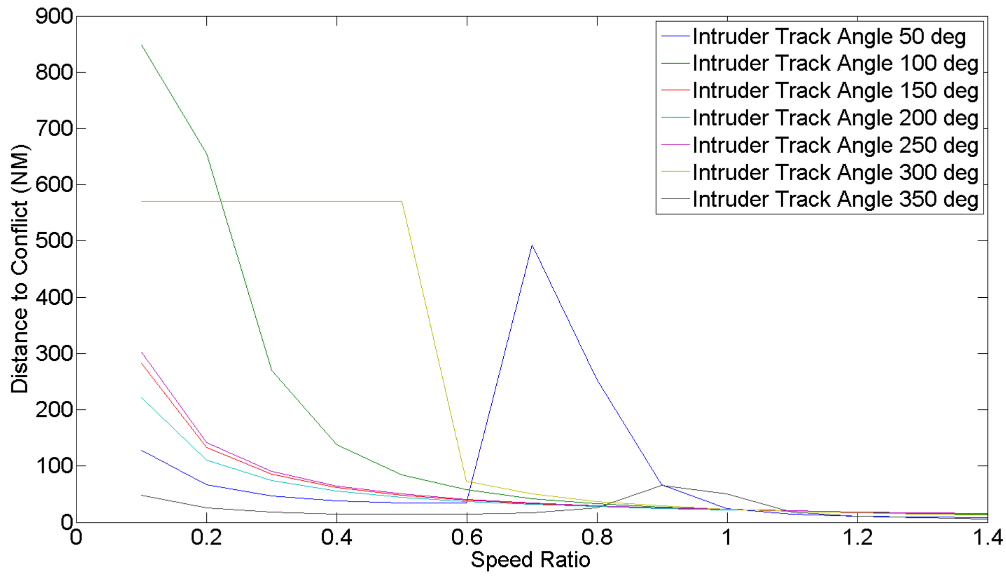

Figure 3-7: Loss of Lateral Resolution Space (30 degrees) at Distance to Conflict for 5 NM ANSD and 850 km/h Reference Speed (Selection)

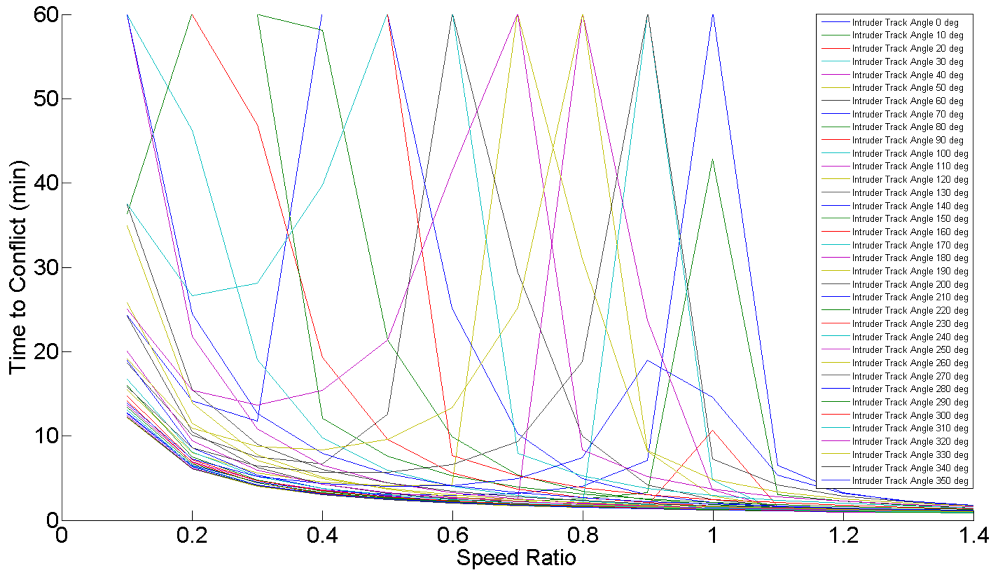

Figure 3-8: Loss of Lateral Resolution Space (30 Degrees) at Time to Conflict for 5 NM ANSD and 850 km/h Reference Speed

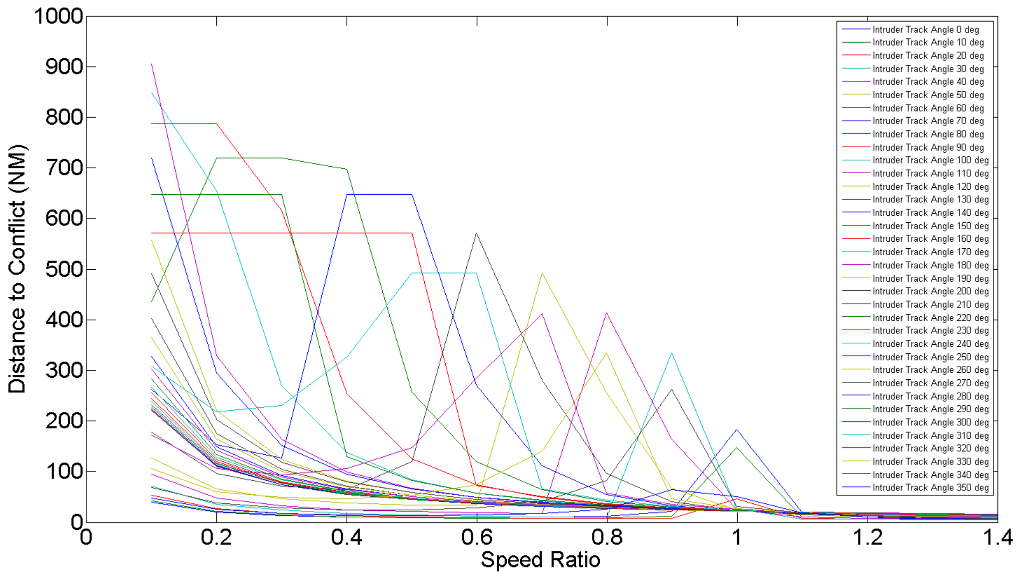

Figure 3-9: Loss of Lateral Resolution Space (30 Degrees) at Distance to Conflict for 5 NM ANSD and 850 km/h Reference Speed

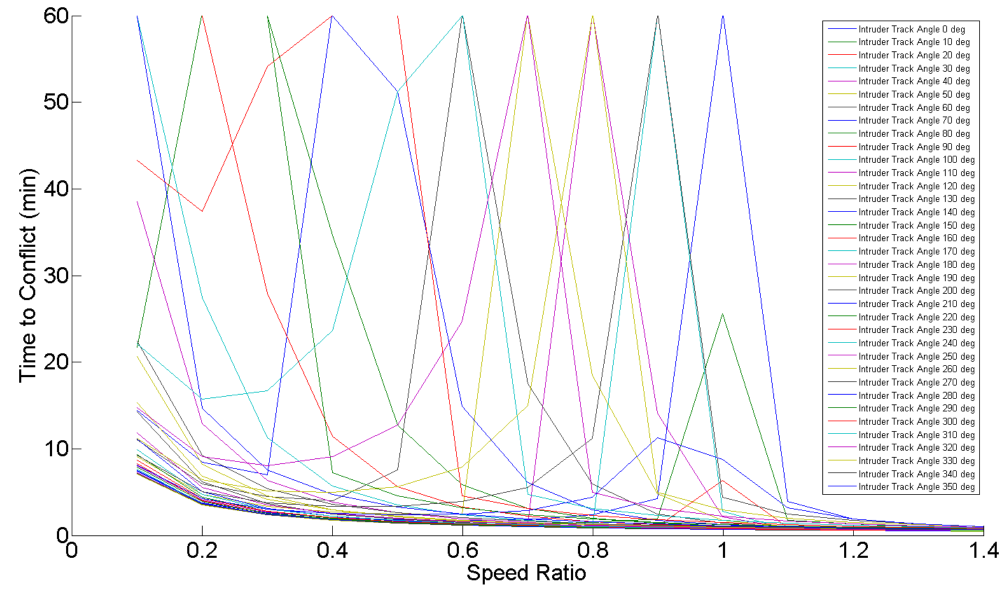

Figure 3-10: Loss of Lateral Resolution Space (30 Degrees) at Time to Conflict for 3 NM ANSD and 850 km/h Reference Speed

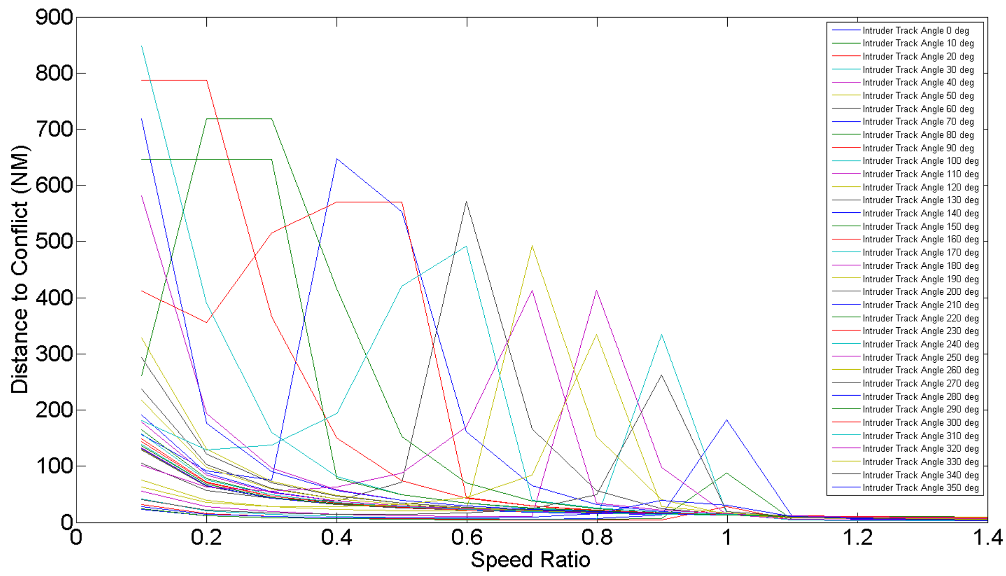

Figure 3-11: Loss of Lateral Resolution Space (30 Degrees) at Distance to Conflict for 3 NM ANSD and 850 km/h Reference Speed

Table 3-1: Combinations of Intruder Track Angle (Horizontal Axis in Degrees) and Speed Ratio (Vertical Axis) in Approach Scenarios with a Laterally Offset CPA Resulting in a Maneuver Advice Reversal Based on the Dot Product Rule

280	290	300	310	320	330	340	350	0	10	20	30	40	50	60	70	80
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	-
-	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	-
-	-	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	-	-
-	-	-	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	-	-
-	-	-	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	-	-	-
-	-	-	-	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	-	-	-	-
-	-	-	-	-	0.8	0.8	0.8	0.8	0.8	0.8	0.8	-	-	-	-	-
-	-	-	-	-	-	0.9	0.9	0.9	0.9	0.9	-	-	-	-	-	-
-	-	-	-	-	-	-	-	1.0	-	-	-	-	-	-	-	-

3-3 Conclusion

Special case scenarios requiring additional rules to resolve by implicit maneuver coordination are symmetrical conflicts and low speed ratio conflicts. In a symmetrical conflict two aircraft approach each other head-on or at an angle where they have an equal ratio between distance to CPA and speed. The implicit maneuver coordination advice direction is then likely to fluctuate. A symmetry breaking algorithm is needed to safely resolve these types of conflicts.

A low speed ratio conflict is defined by ownship having a significantly lower speed than the intruder. The lower the speed ratio, the smaller the resolution space for ownship, in terms of achievable angles for the relative velocity that must be diverted enough by a lateral maneuver to maintain separation.

To resolve these types of conflicts, the look-ahead time in a CD&R algorithm must at least contain the moment in time at which the resolution space runs out. This moment is dependent on speed ratio, reference speed, ANSD, intruder track angle relative to ownship track angle and ownship turn capability. Intruder angle relative to ownship can be divided into two groups, oncoming and overtaking traffic. Conflicts with an intruder approaching from behind cause the maneuver direction advice to be opposite of what is expected from the location of the CPA in the non-relative frame for some combinations of intruder track angle and speed ratio and offer no lateral solution for other combinations when using implicit maneuver coordination. The combinations that have no solution can be resolved by maneuvering in the opposing direction from the maneuver advice. This can only be done when the conflict is not in the critical time window. This window comprises of the time to conflict at which the resolutions space is lost, the final stage of rapid loss of resolution space marked by the gradient passing a threshold, pilot response delay, and additional safety margins.

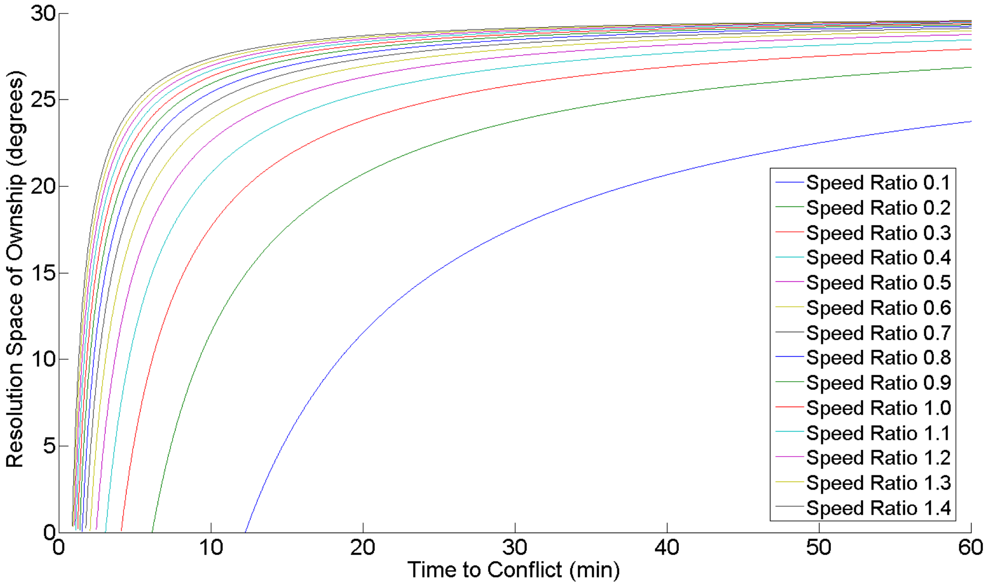

Figure 3-12: Loss of Lateral Resolution Space (30 Degrees) for Different Speed Ratios with an Intruder Angle of 200 Degrees for 850 km/h Reference Speed

Chapter 4

Multiple Intruders

Implicit maneuver coordination has been designed for single intruder scenarios. To apply the same principles to scenarios with multiple intruders, the framework of implicit maneuver coordination must be extended by a rule-based system.

Conflict areas become even more relevant for multiple intruders. Instead of keeping track of the location of all intruders, the conflict areas provide enough information to know whether or not loss of separation will occur and if a maneuver is necessary.

The location and general outline of a conflict area does not follow uniquely from a conflict scenario. An intruder can theoretically approach ownship in a large number of different configurations in terms of distance between aircraft, aircraft attitude and traveling velocity that all lead to the same location and overall shape of the conflict area. Therefore, we can explore implicit maneuver coordination in those types of scenarios by analyzing the conflict areas.

In actual flight there can be infinitely many different conflict scenarios. Ranging from two aircraft on slowly converging flight paths, to a dense airspace with multiple conflicts. To analyze the application of implicit maneuver coordination in multiple intruder scenarios, the different possible scenarios will be categorized. Each category has its own strategy for conflict resolution. This results in the rule-based system that is summarized in a decision tree in section 4-1, which will be further discussed for different numbers of intruders in sections 4-2, 4-3 and 4-4. Four categories will be discussed in case of two or more intruders.

4-1 Decision Tree

The second and third question of section 1-4 are now addressed by analyzing implicit maneuver coordination in scenarios with multiple intruders. The result of this analysis is shown in the decision tree in figure 4-1.

Following the decision tree, the first step in categorizing conflict scenarios is to determine the number of intruders that will need to be dealt with in the near future to prevent loss of

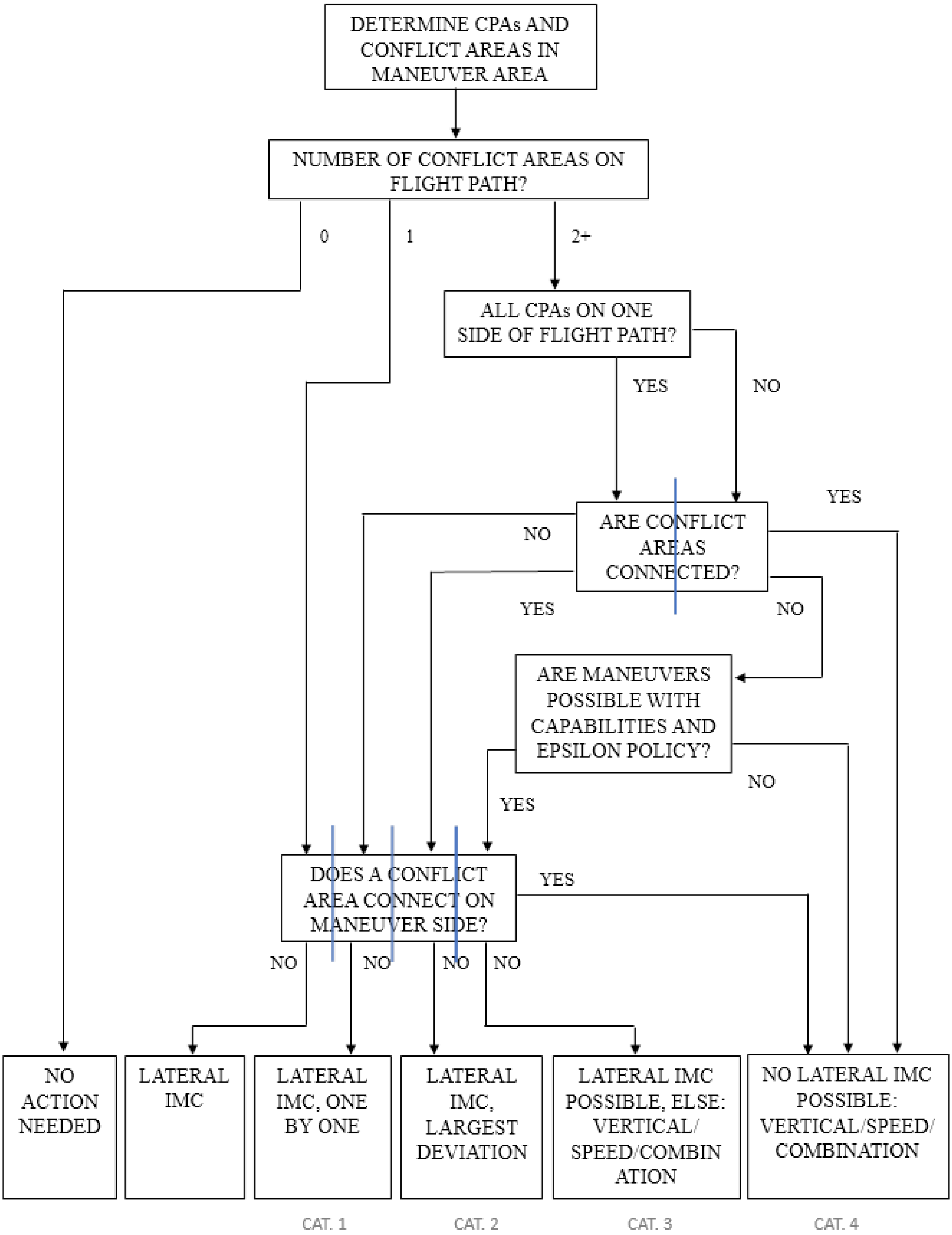

Figure 4-1: Implicit Maneuver Coordination Decision Tree

separation. Considering the horizontal case, the maneuver area is located in front of ownship, limited to both sides by an angle, which depends on ownship turn capabilities and can be varied according to traffic density. Additionally, the area starts at the location of ownship and extends in front to cover the distance that ownship would travel in the chosen look-ahead time. The choice for look-ahead time will likely depend on actual or expected traffic density.

Based on known state information, conflict probing can be used to find the conflict areas. The next step required depends on the number of conflict areas of intruders on the current flight path.

It should be noted that, apart from track angle maneuvers, implicit maneuver coordination also allows for vertical speed maneuvers, ground speed maneuvers, and maneuvers combining these three options [9]. This analysis focuses on lateral maneuvers. The pilot making the maneuver decision likely has the most situational awareness of the horizontal conflict geometry, especially with multiple intruders, when using conflict probes on the navigation display. Also, vertical maneuvers are used for longer term separation by ATC and should remain available under normal circumstances for last-minute collision avoidance maneuvers by TCAS. Finally, preferring lateral maneuvers should make maneuvers more predictable.

4-2 No Intruders on Flight Path

In case there are no conflict areas on the current flight path, no action is needed in terms of separation assurance. Conflict areas in the maneuver area that do not touch the current flight path are of no immediate concern. A safety margin is built into the separation distance that determines where a loss of separation occurs and therefore the location of the conflict areas' outline.

4-3 One Intruder on Flight Path

Apart from the special cases already described, scenarios involving one intruder with a conflict area that touches or overlaps the current ownship flight path can be easily solved by using implicit maneuver coordination. With a single intruder this means turning away from the CPA using a track angle that ensures minimum separation will be maintained.

4-4 Two or More Intruders on Flight Path

When more than one intruder is present it becomes much more complicated to solve all conflicts. To decide on the action needed in a specific case, we can classify all possible scenarios into four different categories. For purposes of classification and determining the required strategy, it does not matter how many additional intruders are present beyond the first two. Example scenarios can be given for every category that consists of only two intruders and although adding another intruder can change the category, it does not change the categorization factors.

4-4-1 Categorization Factors

Scenarios can be grouped into one of four categories made from combinations of the following two factors:

- **Location of CPAs**
  The location of the CPAs in relation to ownship flight path. They can either all be located on one side of the flight path, or at least one on each side.
- **Connection Between Conflict Areas**
  Whether or not the conflict areas are connected. Two conflict areas are considered to be connected if they touch or overlap.

4-4-2 Category 1

The first category and least complex case is when all CPAs of intruders with conflict areas on ownship flight path are on one side of the flight path and the conflict areas are not connected. An example of a category 1 conflict scenario is shown in figure 4-2. When these conditions are met, all conflicts can be treated individually as single intruder scenarios and laterally resolved one by one using implicit maneuver coordination. By only maneuvering for the next predicted conflict, unnecessary maneuvers are prevented. As state information is updated, due to a maneuver or other change in speed or position, the location of the conflict areas will also change so a conflict further away from ownship may no longer be present.

4-4-3 Category 2

The second category contains scenarios also with all CPAs of intruders with conflict areas on the current flight path on one side of the flight path, but with the conflict areas connected. An example of such a scenario is shown in figure 4-3. The conflicts can be treated as one large conflict that can be solved by a large lateral maneuver to the combined conflict area. By calculating tangents to all the individual conflict areas that are part of the connected conflict area and selecting the largest deviation from the current ownship track angle to the correct side, opposite of the side that contains the CPAs, this type of scenario can also be solved with a lateral maneuver using implicit maneuver coordination.

4-4-4 Category 3

The third category consists of scenarios with one or more CPAs of intruders with conflict areas on the flight path on each side of ownship flight path, with the corresponding conflict areas not connected. A third category scenario is shown in figure 4-4. Since the conflict areas are unconnected, the conflicts can theoretically be dealt with individually using implicitly coordinated lateral maneuvers. Note that a maneuver will change the location of CPAs and conflict areas. In case the CPAs are relatively close to ownship flight path, the first maneuver can cause all CPAs to be moved to one side of the new flight path, the scenario is now one of the first category. However, this maneuver is in the direction that is not allowed by to

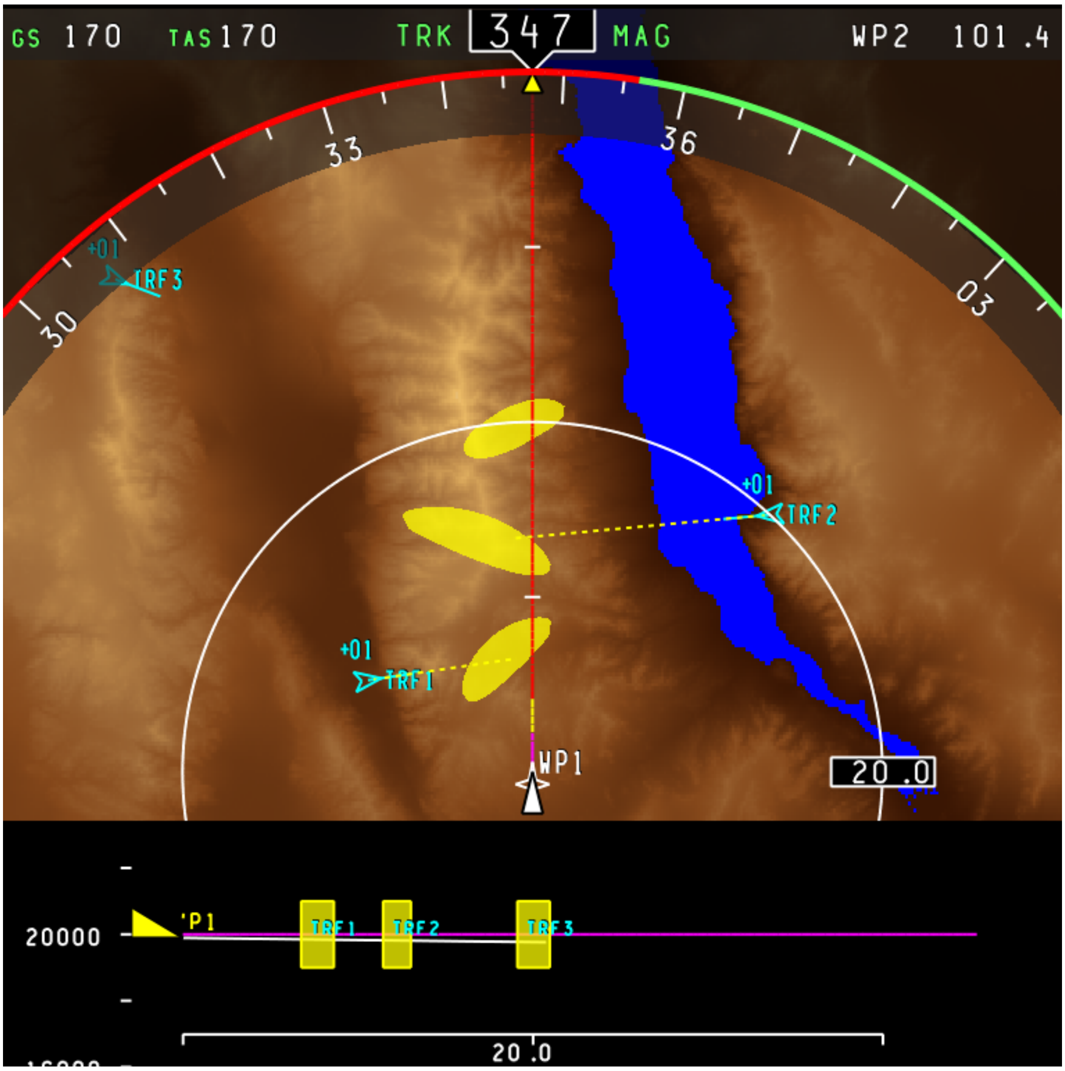

Figure 4-2: Example Scenario with CPAs on one Side and Unconnected Conflict Areas (Category 1)

the dot product policy for all conflicts that belong to a CPA that moves to the other side of the flight path. Therefore, this should only be done when a maneuver is not yet considered, meaning the conflict must not be in the critical time window as discussed in section 3-2-2.

If the CPAs are not close to ownship flight path, sharp turns may be necessary to maintain intruder separation, meaning it will depend on ownship capabilities whether or not the conflicts can be solved laterally using implicit coordination. If this is not possible, the alternative is to make a vertical maneuver, change in speed, or a combination, in compliance with implicit maneuver coordination criteria.

4-4-5 Category 4

A scenario is placed in the fourth category when it has one or more CPAs on each side of ownship flight path and conflict areas that correspond with the CPAs that are connected. An

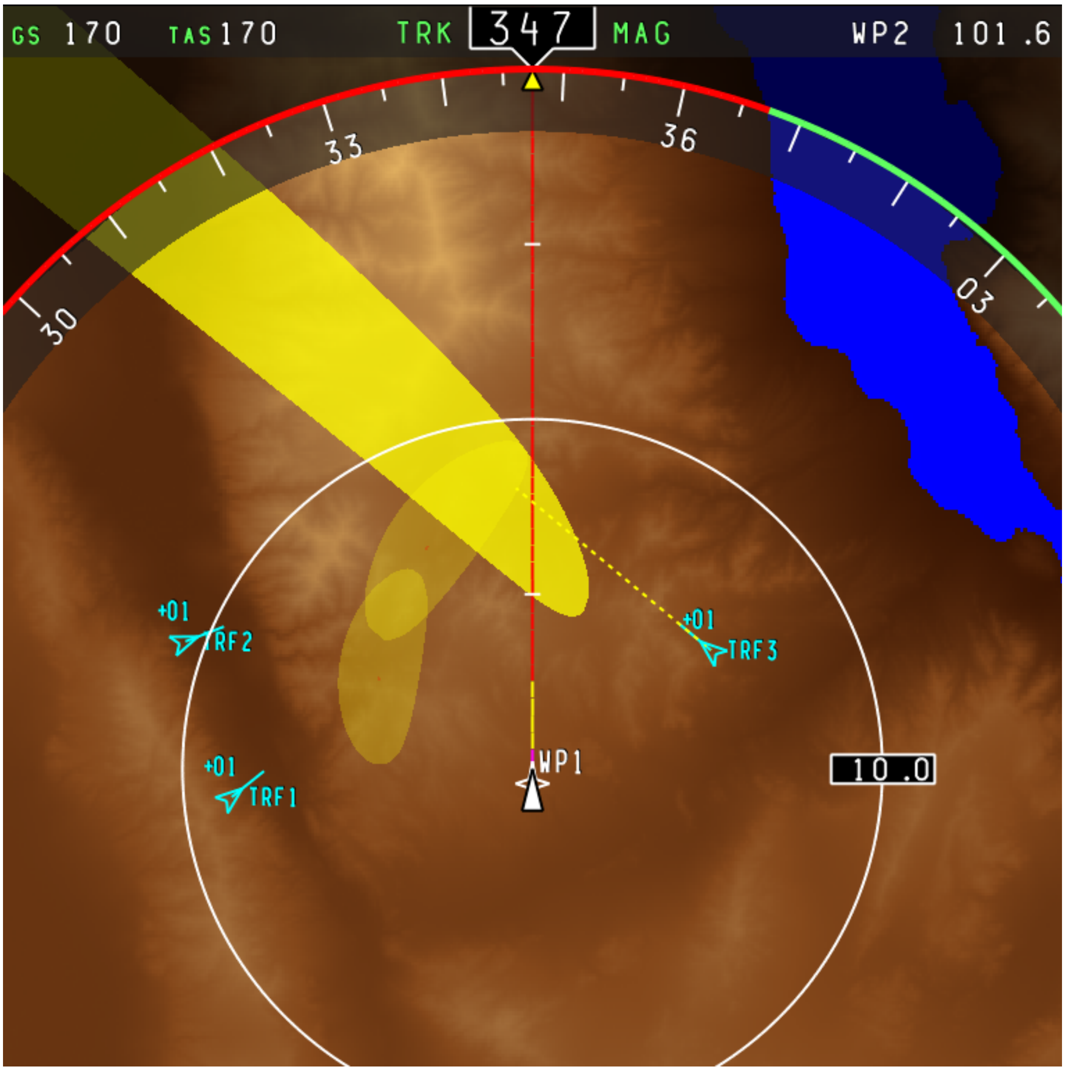

Figure 4-3: Example Scenario with CPAs on one Side and Connected Conflict Areas (Category 2)

example is shown in figure 4-5. Such a scenario cannot be solved by lateral maneuvers based on implicit maneuver coordination, unless it is outside of the critical time window (see section 3-2-2) and a maneuver can be made in a direction that goes against the implicit maneuver coordination advice. The alternative options are again a vertical maneuver, speed change, or a combination. As can be seen from the decision tree, if there is a conflict area that connects to another conflict area on the maneuver side, the maneuver would lead to loss of separation with another intruder, so a lateral maneuver is no longer an option. This is why under this condition scenarios otherwise belonging to another category, should also be placed in the fourth category.

It is possible for a scenario to consist of a combination of different categories. For example, it can have two unconnected conflict areas with CPAs on one side within five miles and two connected conflict areas with a CPA on each side at a twelve mile distance. These should then be considered as separate scenarios. When different types of scenarios are closer

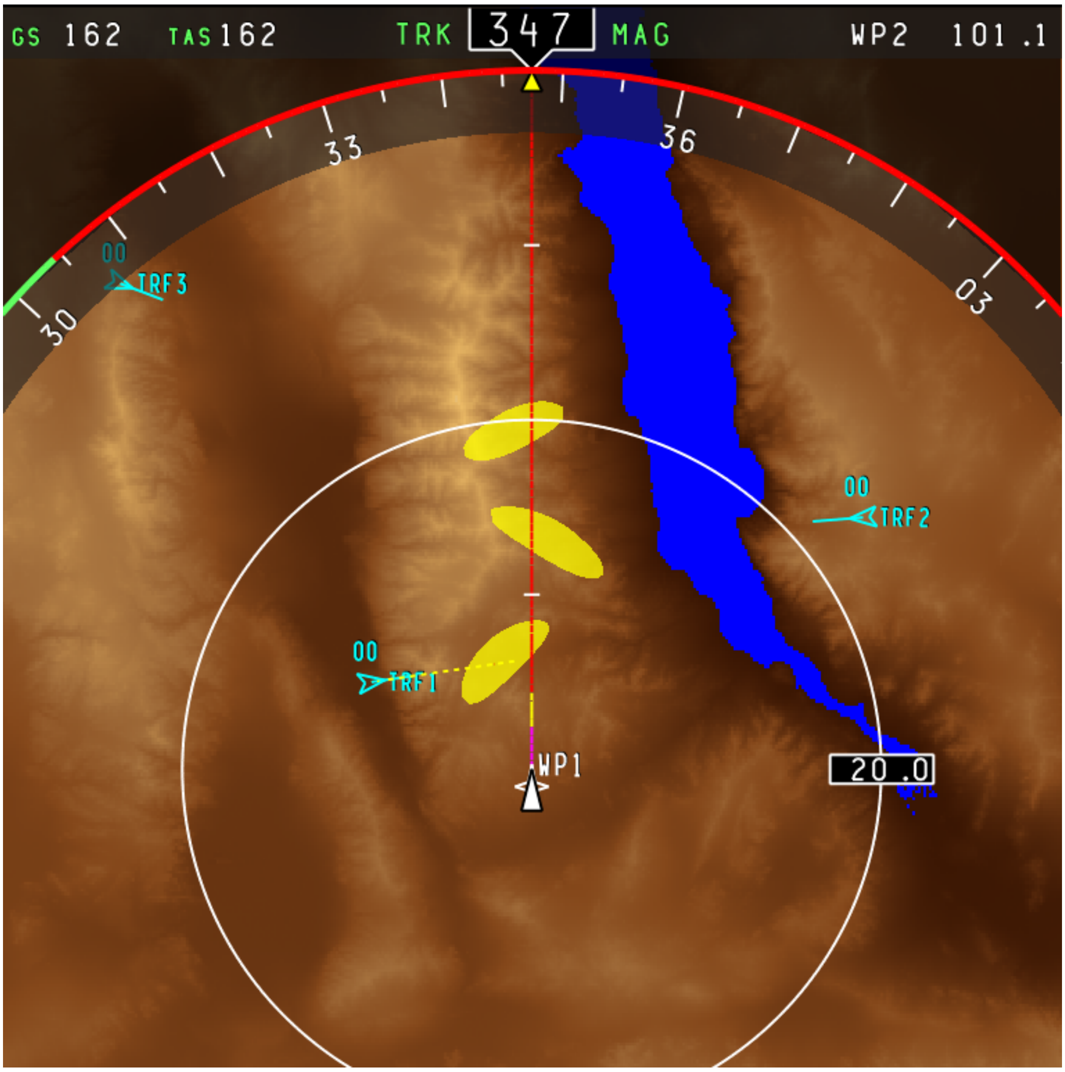

Figure 4-4: Example Scenario with CPAs on Both Sides and Unconnected Conflict Areas (Category 3)

together, they should be considered as one scenario of the highest category represented.

Inherent to such a classification system, scenarios can be defined that do not clearly belong to a specific category. For example, a scenario with CPAs on both sides of the flight path with only some of the conflict areas connected. One method to deal with such a scenario is to treat it as separate scenarios of which some have all conflict areas connected and the remaining have none.

4-5 Conclusion

Implicit maneuver coordination can be extended to conflict scenarios containing multiple intruders with categorization based on CPA locations and connection between conflict areas.

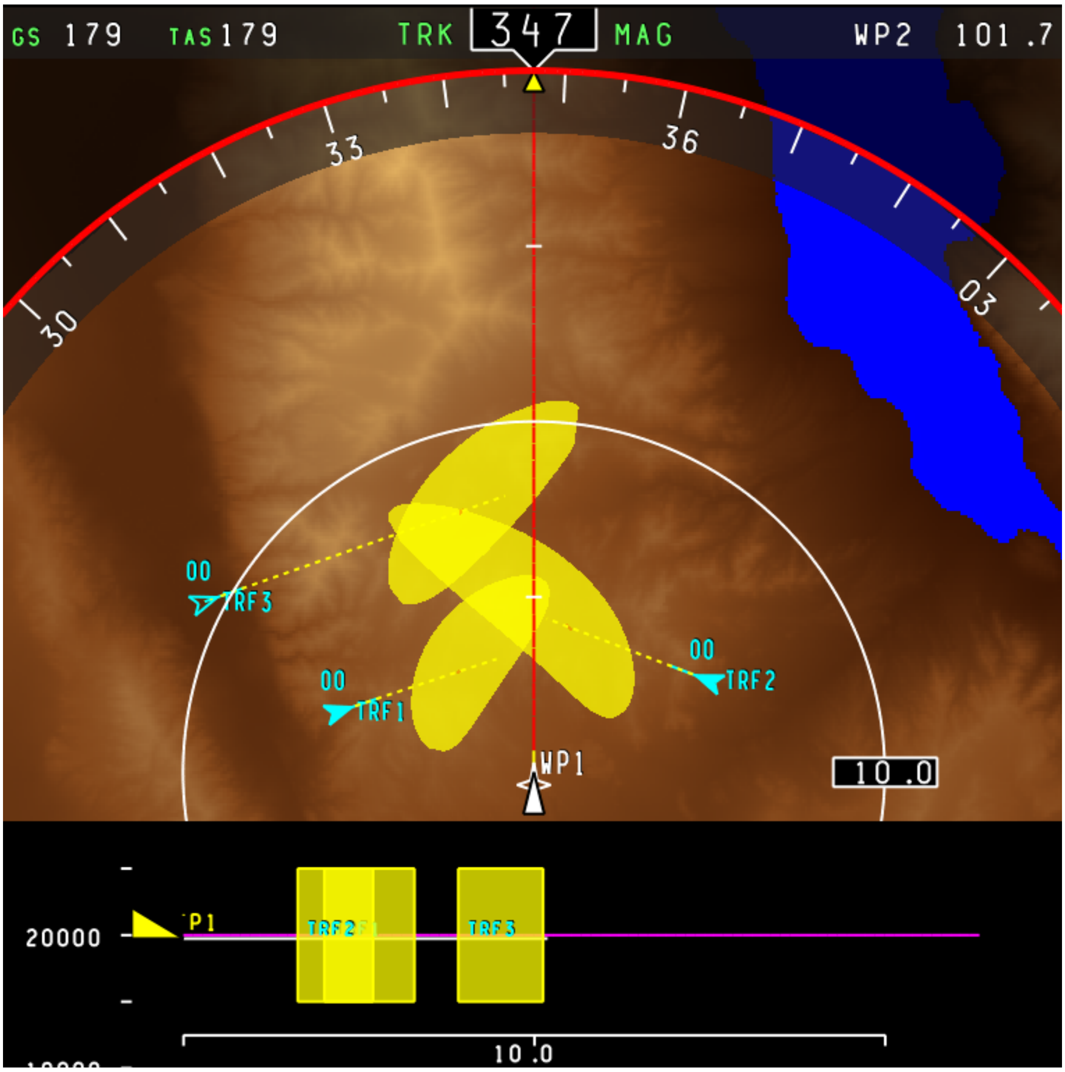

Figure 4-5: Example Scenario with CPAs on Both Side and Connected Conflict Areas (Category 4)

Category 1 has CPAs on one side of the flight path and no connected conflict areas. The conflicts can be treated as single intruder scenarios and solved one by one with a lateral maneuver in the direction that follows from implicit maneuver coordination.

Category 2 has CPAs on one side and connected conflict areas. It can be treated as a single combined conflict and resolved by a lateral maneuver.

Category 3 has CPAs on both sides of the flight path and unconnected conflict areas. Conflicts in this category can typically be dealt with individually by a lateral maneuver, in some cases this is not possible due to the specific conflict geometry and limitations in ownship maneuvering capabilities.

Category 4 has CPAs on both sides and connected conflict areas. It is only possible to solve these scenarios with a lateral maneuver based on implicit maneuver coordination if the conflicts are not in the critical time window.

Chapter 5

Implementation

This chapter will address question four from section 1-4 and look at the data processing implications that follow from the categorization process described in chapter 4. The blocks in the decision tree from section 4-1 are not guaranteed to have a function available for implementation. Section 5-1 will dissect the algorithm that can be used to implement the decision tree. Section 5-2 will then discuss different options to implement the algorithm.

5-1 Algorithm

The pseudo code for the decision tree from section 4-1 can be found in appendix A. It relies on a function **Confl_areas** that uses state data $(\boldsymbol{s}, \boldsymbol{v})$ to compute the location of CPAs, their conflict areas and the number of conflict areas that intersect or connect to the current flight path and in the current maneuver area. When that is completed, the function **Categorize** uses these results to decide the category the current scenario is placed in. Function Categorize tests whether all CPAs belonging to conflict areas on the current flight path are on one side or not. Then the category is determined by using three additional functions:

- **Confl_areas_connected** is used to verify whether or not all conflict areas are touching or connected. A human operator can easily see this from the navigation display, however, for a computer algorithm this is not so straightforward. In the next section it will be discussed why the current setup does not allow for easy computation of connectedness of the conflict areas.
- **Confl_area_blocking** handles the block in the decision tree that checks if a conflict area connects on the maneuver side, effectively blocking a lateral maneuver to that side.
- **Maneuver_possible** represents part of the categorization that determines if a lateral maneuver is possible based on the specific geometry and ownship capabilities.

5-2 Implementation Options

A task that is very simple for a human operator is not always easily automated. Here the algorithm must determine whether two conflict areas are connected or touching, which a human can do in a single glance. The algorithm can not be efficiently implemented without a method to enable a machine to make the same assessment. There are several options to make this possible that follow in the next three sections. The implementation of the function that determines whether or not a maneuver is possible based on geometry and aircraft capabilities is beyond the scope of this thesis.

5-2-1 Intersection of Line Segments

The first possible method for implementing an automatic check for connection between conflict areas is demonstrated in figure 5-1. The points where separation is lost and regained are stored and for each conflict area, the closest points on adjacent test vectors are connected by a line. In the example the points belonging to the left conflict area are connected by a green line and the area on the right by a blue line. Thus going through all the points, the result is a set of line segments that form a piece-wise linear approximation of the actual conflict area. For each line segment, a line equation is then formulated. Whenever two line segments from different conflict areas intersect, based on intersection points from the line equations, the areas are connected. These intersections are found at the point where the two test vectors are on different sides of the actual point of intersection between the conflict areas, as seen in the figure.

A downside to using this method is that two conflict areas that touch but are not overlapping will not be detected. Also, a conflict area that is completely enclosed in another area will not be detected, since no line segments will intersect. Although a conflict that has a conflict area completely enclosed in another area does not add complexity to the conflict scenario, it still must be detected as connecting to make sure the scenario is correctly categorized.

5-2-2 Points on Vector

The next method that can be used is to analyze the separation loss and restore points along each test vector, as shown in figure 5-2. Again, green in this figure is used for the left conflict area and blue for the right, in this case to signify which area the specific points belong to. For this method the points are also saved. Two conflict areas are connected if at least one point of loss or restore of one of the areas is located between a loss and a regain point of the other.

This method has some advantages over the previous method. Connectedness can be determined even from a single test vector that crosses the overlapping section of the two conflict areas. No calculations are needed. Furthermore, areas that are completely encased are also detected by this method.

Areas that are only touching can be detected when there is sufficiently high resolution for the test vectors covering the area. Since all vectors are diverging from each other away from ownship, the closer to ownship the higher the density and thus the higher the resolution of the conflict probes.

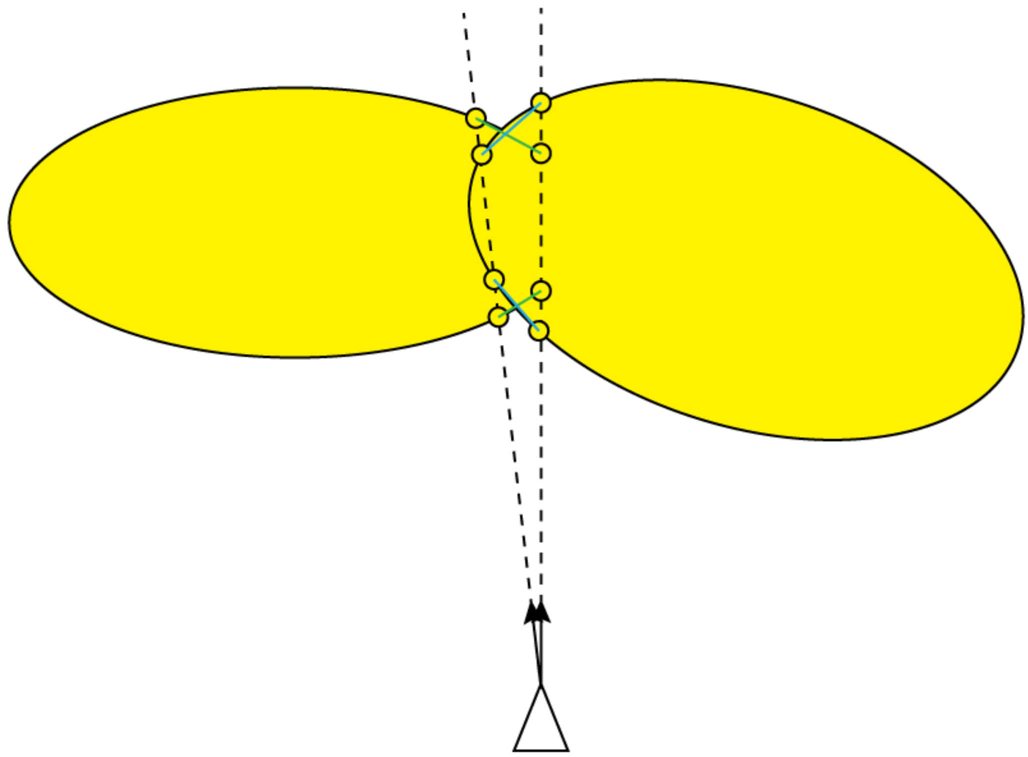

Figure 5-1: Determine Connectedness of Conflict Areas By Intersecting Line Segments

5-2-3 Approximate by Ellipses

The final method is to model the conflict areas as an ellipse, exemplified in figure 5-3. C is the center of the ellipse, at the coordinates (x_0, y_0). F_1 and F_2 are the foci, which are separated by a distance of 2c, r_1 and r_2 are the distance from F_1 and F_2, respectively, to a point on the ellipse. The ellipse is the curved line that is a closed loop consisting of the set of all points that satisfy equation 5-1 and 5-2.

$$r_1 + r_2 = 2a \tag{5-1}$$

$$\frac{(x - x_0)^2}{a^2} + \frac{(y - y_0)^2}{b^2} = 1 \tag{5-2}$$

with a and b, the radius along the x and y axis, respectively. Note these equations are only valid for ellipses aligned with the coordinate plane, spherical coordinates must be used for conflict areas if the major and minor axis of the approximation ellipse are not parallel to the coordinate system. As can be verified by the example scenarios throughout this thesis, most conflict areas can be approximated by an ellipse with relatively small errors. The approximation errors become even less relevant if only the relative closeness of conflict areas is to be determined, which is a possible refinement of the categorization algorithm.

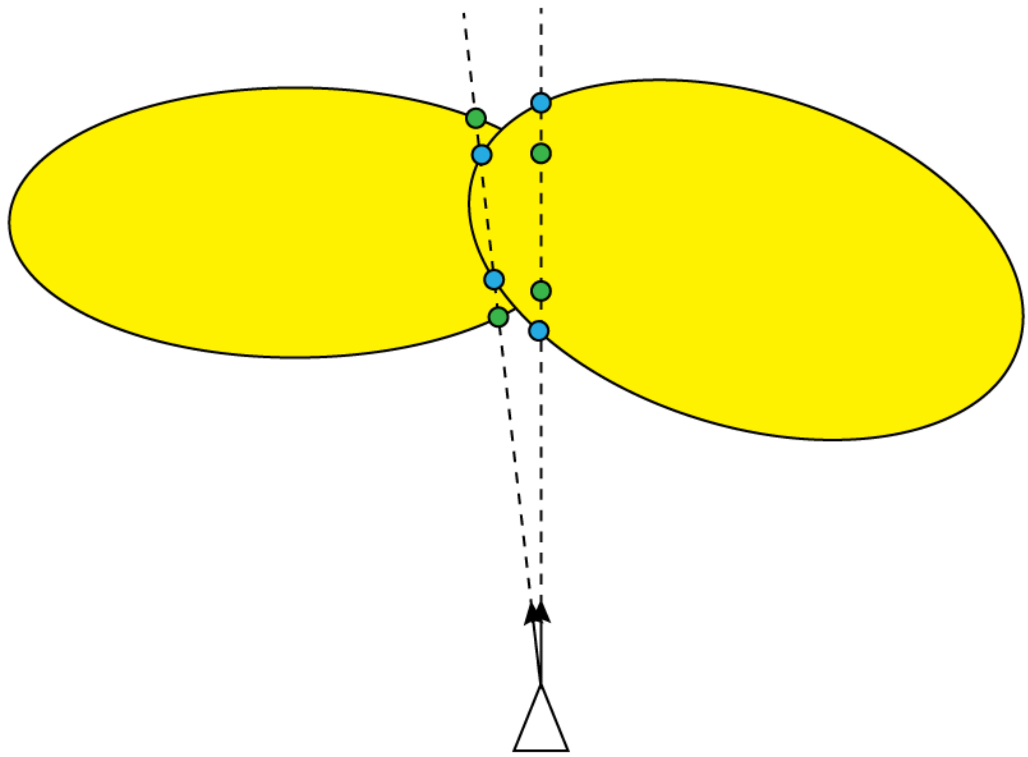

Figure 5-2: Determine Connectedness of Conflict Areas By Analyzing Points on Test Vectors

This method provides a simple mathematical solution: once the ellipse equations that most closely approximate the actual conflict areas are found, it is a simple operation to verify if they are connected, overlapping or even in close vicinity.

Low speed ratio conflicts have atypical conflict areas that can not be modeled by an ellipse with small approximation error and need to be treated separately.

5-3 Conclusion

Data processing for categorization used to apply implicit maneuver coordination on multiple intruder scenarios requires certain non-trivial functions to be implemented. A function verifying if conflict areas are connected, a function determining if a conflict area is blocking a maneuver in that direction, and a function that returns whether a lateral maneuver is possible based on conflict geometry and aircraft capabilities.

Three methods have been presented to implement a function that verifies if conflict areas are connected: determine whether line segments approximating the conflict areas intersect, analyze separation loss and restore points along test vectors, and approximation of conflict areas by ellipses.

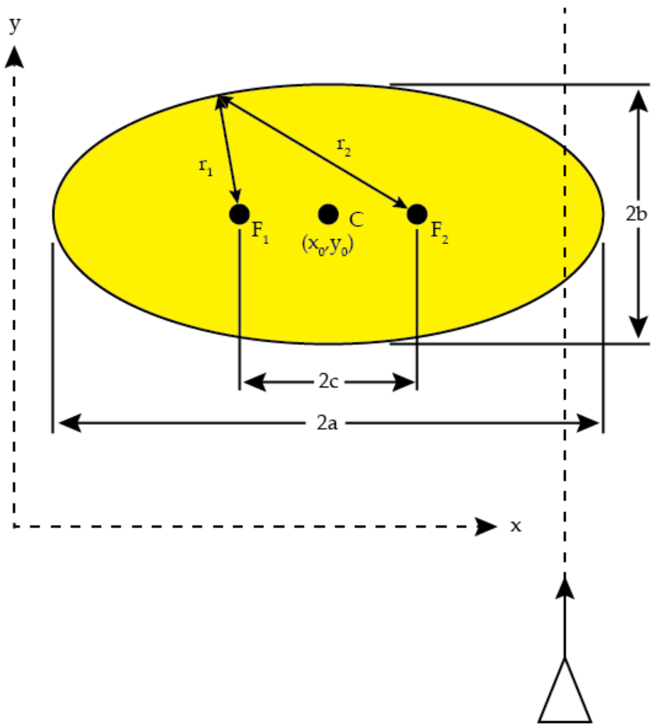

Figure 5-3: Ellipse Approximation of a Conflict Area to Determine Connectedness

Chapter 6

Applications

Some of the possible applications of the solution for low speed ratio encounters from section 3-2-2 and the categorization system from chapter 4 will be discussed in this chapter. The most important application is separation assurance in section 6-1, then the final question from section 1-4 on maximum airspace density is addressed in section 6-2, followed by applications in preventive maneuvers, planning routes, and maneuver timing in sections 6-3, 6-4, and 6-5.

6-1 Separation Assurance

The rule-based extension to implicit maneuver coordination for multiple intruders based on scenario categorization from chapter 4 is designed primarily for separation assurance. The higher the category, the more complicated it becomes to solve all conflicts in the scenario. A support algorithm based on categorization can be used by pilots to get a quick idea of the scenario complexity and what resolution method to use. The pilot can then be shown the conflict areas with the possible resolution options and which option is preferred. Also, the pilot can be alerted to intruders with conflict areas near the flight path that could quickly cut off large parts of the resolution space with minor changes in speed or heading.

6-2 Maximum Airspace Density

In section 3-2-2, the minimum distance to conflict at which a lateral maneuver must be made is shown to depend on speed ratio, reference speed, intruder track angle relative to ownship track angle, ANSD, and ownship turn capability. The minimum separation distance needed between aircraft for safe flight that allows for self-separation can be found from the distance traveled within the critical time window (see also section 3-2-2). The main component of the critical time window is the distance to conflict at which the lateral maneuvering space is lost, shown in figures 3-8, 3-9, 3-10, and 3-11. Maximum airspace density for which implicit maneuver coordination can still be applied for self-separation follows from these minimum separation distances.

6-3 Preventive Maneuvers

If one or more conflict areas are detected before the start of the critical time window, the pilot or operator can decide to make a preventive maneuver to ensure a low-complexity scenario. For example, a small turn can be made to move all CPAs to one side of the flight path.

6-4 Planning Routes

Multiple intruder scenario categorization can also be used to plan aircraft routes for optimal use of airspace while maintaining safe maneuvering options in case a conflict arises. This principle can be illustrated by comparing two types of traffic geometries. The first is shown in figure 6-1. Lining up aircraft in such a way appears to make efficient use of airspace while still allowing conflict solving. Following the decision tree this turns out to be a category 2 conflict scenario. Improving the conflict solving properties of this geometry, the aircraft can be spaced further apart resulting in unconnected conflict areas and the category 1 scenario shown in figure 6-2. In other words, robustness can be used as a criterion in planning aircraft routes.

6-5 Maneuver Timing

In any conflict and especially in low speed ratio conflicts, the pilot or operator must be aware of the development of the conflict in time and the effect this will have on his resolution space. As has been previously researched and implemented, a timer can be shown on the navigation display allowing the pilot to see the stage the current conflict is in to ensure correct maneuver timing. An implementation of such a timer on a primary flight display in the simulator is shown in figure 6-3. Also, the current flight path can be colored to corresponds to the different stages of the conflict. An implementation of this latter option can be seen in the various figures in this thesis taken from the navigation display in the simulator.

6-6 Conclusion

Some applications of classification and solution for low speed ratio conflicts are discussed. Categorization can be used as a supporting algorithm for pilots to analyze conflict scenarios and assess, advice or decide on maneuver options. The maximum airspace density for which implicit maneuver coordination can still be applied for self-separation follows from minimum separation distances based on the distance traveled within the critical time window. Conflict scenario categorization can also be used to perform preventive maneuvers to ensure a low-complexity scenario, or to plan routes improving the conflict solving properties of any arising conflicts. As have been previously researched and implemented, a navigation display timer or coloring of the flight path can be used to make the pilot aware of the stage of the current conflict to ensure correct maneuver timing.

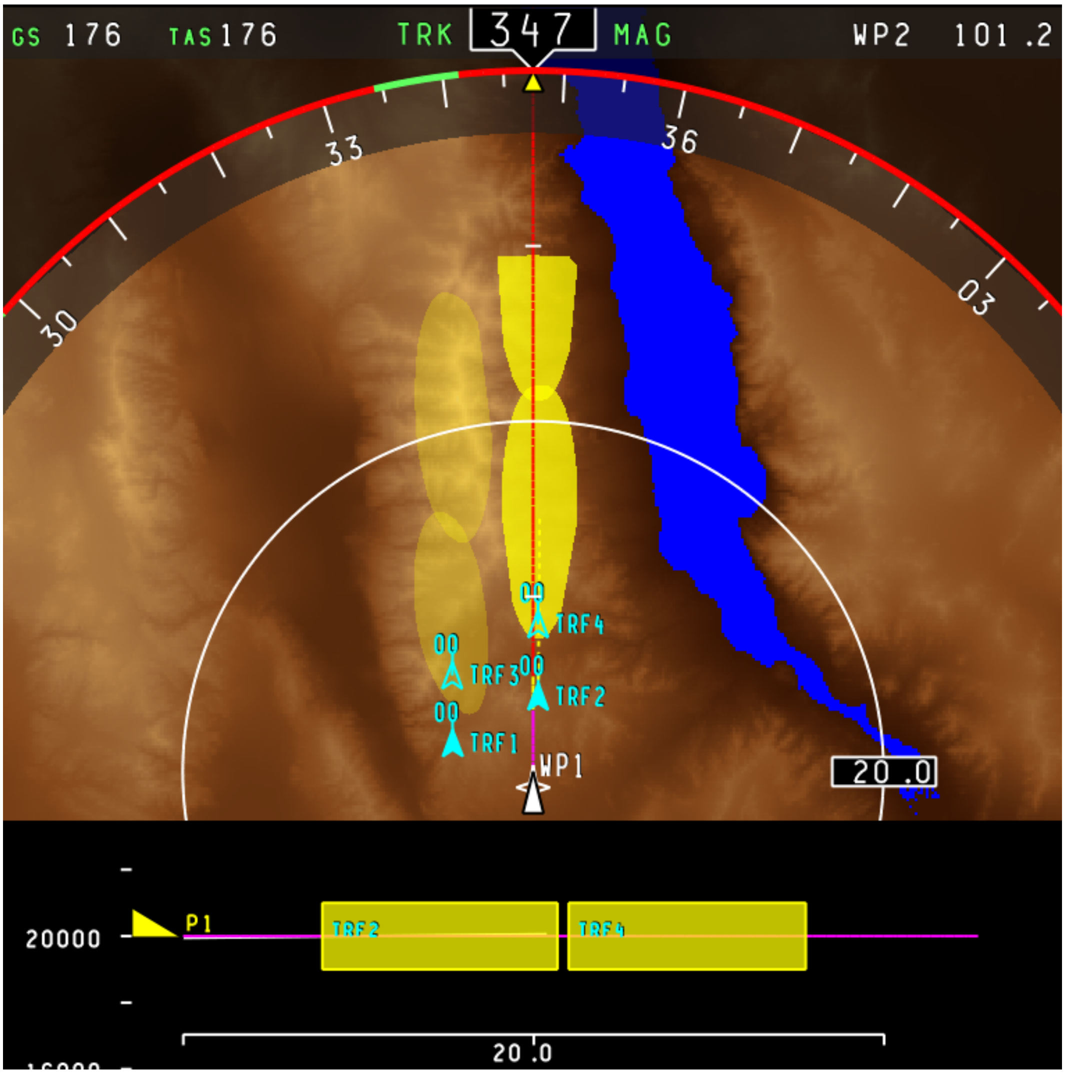

Figure 6-1: Category 2 Conflict Scenario

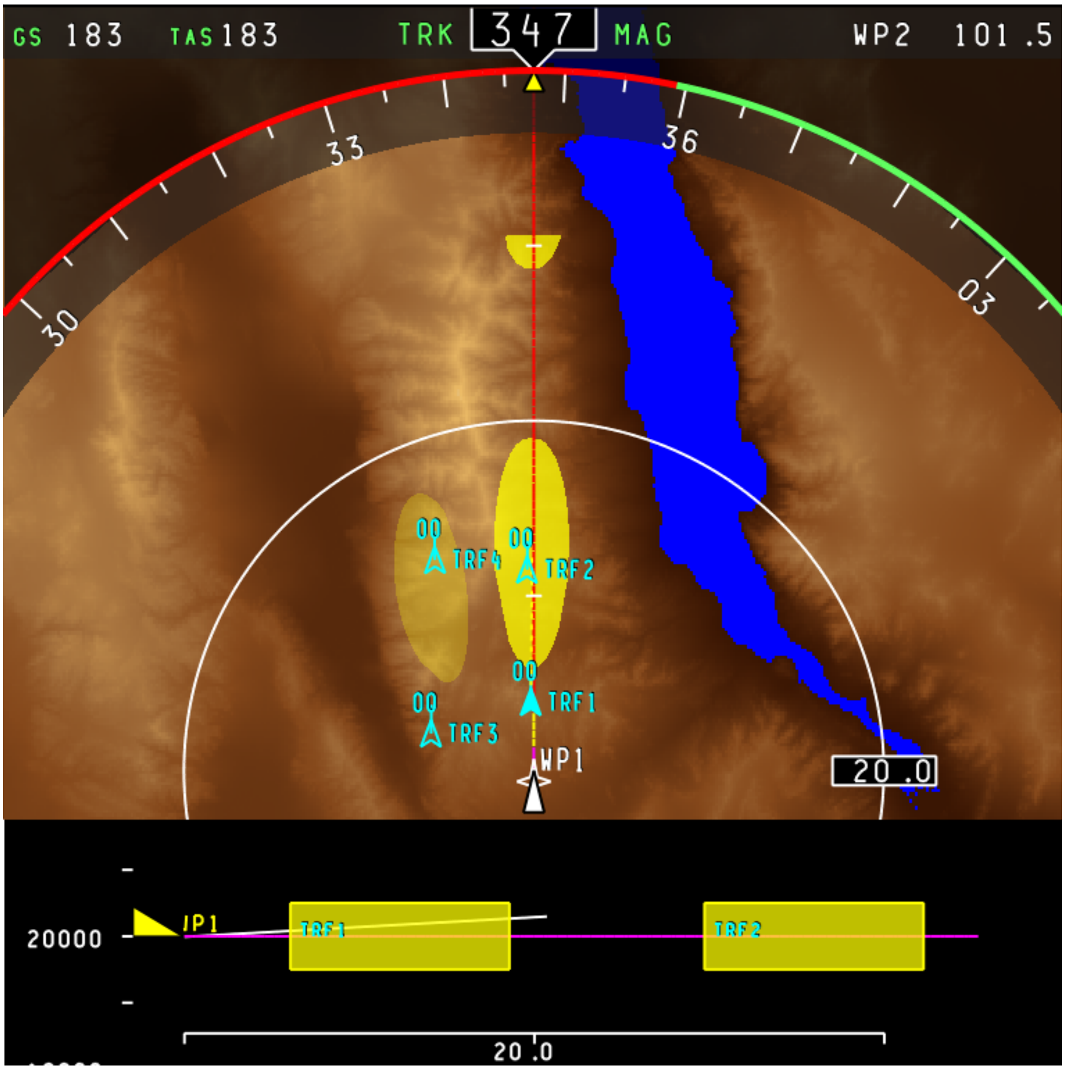

Figure 6-2: Route Planning Resulting in a Category 1 Scenario

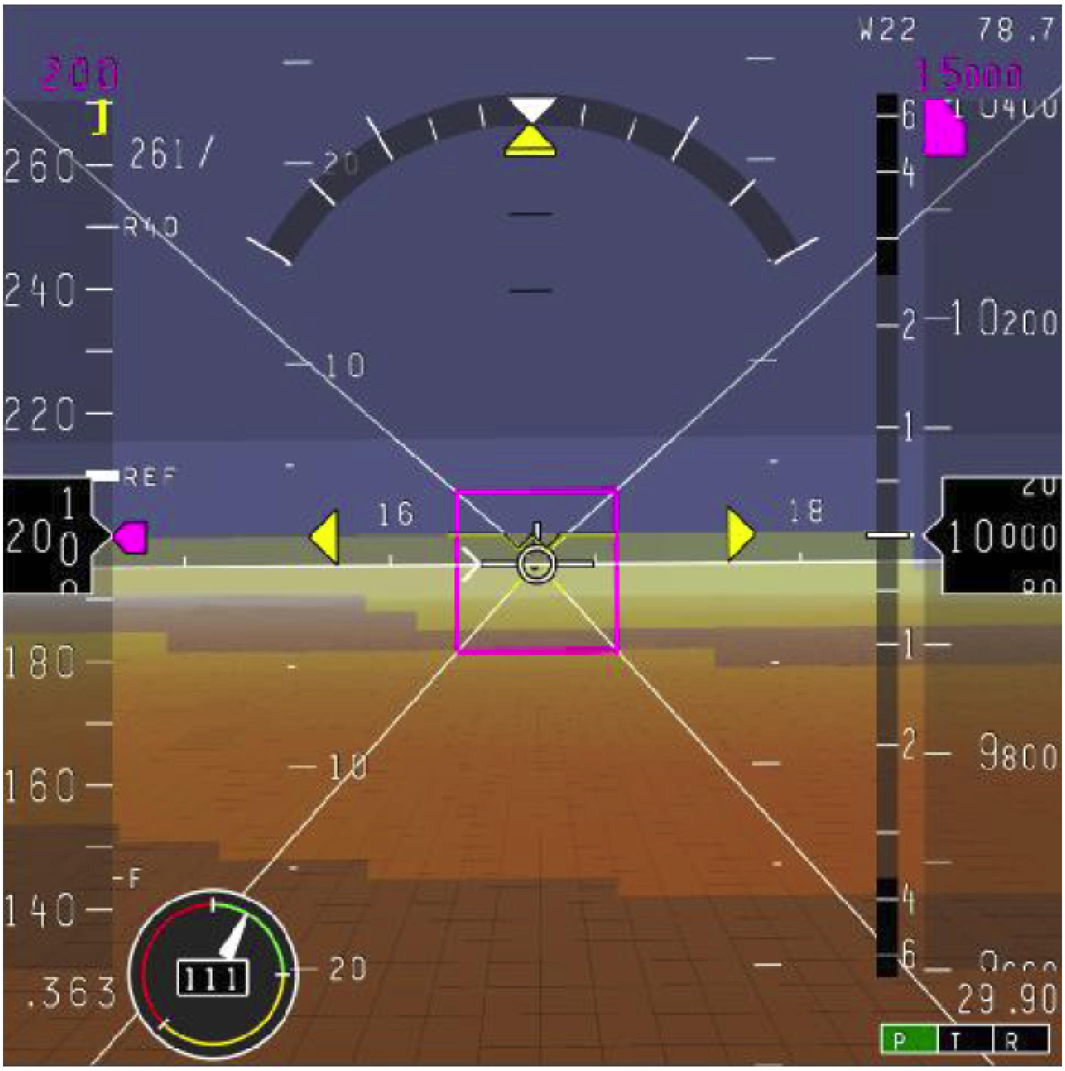

Figure 6-3: Maneuver Timer on a Primary Flight Display

Chapter 7

Conclusion

The conclusions from the research described in this thesis are presented in section 7-1, followed by a summary of the scientific contributions in section 7-2. Finally, recommendations for future research can be found in section 7-3.

7-1 Conclusion

If pilots are expected to receive some separation responsibilities, maneuvers must be coordinated to ensure they are complementary. Maneuvers performed by pilots for self-separation are preferred to be lateral. These maneuvers can be implicitly coordinated between aircraft based on a horizontal criterion that contains the requirements for the minimum angle of the velocity vector ownship should choose to prevent loss of separation. The criterion also contains a coordination variable ϵ that determines the maneuver direction and ensures different algorithms are implicitly coordinated. The dot product policy for ϵ that bases the maneuver direction on the dot product of the relative position and velocity is preferred since it results in minimal and safe maneuvers. Since tangential resolution algorithms were shown to satisfy the horizontal criterion in [10], conflict areas resulting from conflict probes can be used to find the minimum lateral maneuver used for implicit maneuver coordination. The maneuver direction given by the dot product policy can also be obtained from the location of the closest point of approach relative to ownship flight path. [**Chapter 2.**]

Special case scenarios requiring additional rules to resolve by implicit maneuver coordination are symmetrical conflicts and low speed ratio conflicts. In a symmetrical conflict two aircraft approach each other head-on or at an angle where they have an equal ratio between distance to CPA and speed. The implicit maneuver coordination advice direction is then likely to fluctuate. A symmetry breaking algorithm is needed to safely resolve these types of conflicts. A low speed ratio conflict is defined by ownship having a significantly lower speed than the intruder. The lower the speed ratio, the smaller the resolution space for ownship, in terms of achievable angles for the relative velocity that must be diverted enough by a lateral maneuver to maintain separation. To resolve these types of conflicts, the look-ahead time in a CD&R algorithm must at least contain the moment in time at which the resolution space runs out. This moment is dependent on speed ratio, reference speed, ANSD, intruder track angle relative to ownship track angle and ownship turn capability.

Certain combinations of speed ratio and intruder track angle have no solution using implicit maneuver coordination but can be resolved by maneuvering in the opposing direction from the maneuver advice. This can only be done when the conflict is not in the critical time window. This window comprises of the time to conflict at which the resolutions space is lost, the final stage of rapid loss of resolution space marked by the gradient passing a threshold, pilot response delay, and additional safety margins. [**Chapter 3.**]

Implicit maneuver coordination can be extended to conflict scenarios containing multiple intruders with a set of rules that categorizes scenarios based on CPA locations and connection between conflict areas. [**Chapter 4.**]

Data processing for categorization used to apply implicit maneuver coordination on multiple intruder scenarios requires certain non-trivial functions to be implemented. Three methods are presented to implement a function that verifies whether or not conflict areas are connected:

- Determine whether line segments approximating the conflict areas intersect.
- Analyze separation loss and restore points along test vectors.
- Approximation of conflict areas by ellipses.

[**Chapter 5.**]

Some applications of classification and possible solution for low speed ratio conflicts are discussed. Categorization can be used as a supporting algorithm for pilots to analyze conflict scenarios and assess, advice or decide on maneuver options. The maximum airspace density for which implicit maneuver coordination can still be applied for self-separation follows from minimum separation distances based on the distance traveled within the critical time window. Conflict scenario categorization can also be used to perform preventive maneuvers to ensure a low-complexity scenario, or to improve robustness against disturbances when planning aircraft routes. Correct maneuver timing can be ensured by a navigation display timer or coloring of the flight path, as have been previously researched and implemented, to make the pilot aware of the stage of the current conflict. [**Chapter 6.**]

7-2 Summary of Contributions

This thesis contains the following scientific contributions:

- Demonstration of the use of conflict areas and CPAs for implicit maneuver coordination;
- Analysis and possible solution for symmetrical and low speed ratio conflict scenarios;
- Estimation of resolution space loss at time and distance to conflict from simulated approaches with varying speed ratio and relative track angle between ownship and intruder;

- Extension of implicit maneuver coordination framework to multiple intruder scenarios by a rule-based system that categorizes scenarios based on location of CPA and connection between conflict areas.

7-3 Recommendations

The following recommendations are made for future research:

- Effectiveness and efficiency of the categorization process as a support tool to quickly analyze scenarios and advice on maneuver options can be studied in simulations using different encounter models. The performance when used by pilots to resolve conflicts can be measured to see if the system increases safety and efficiency when making self-separation maneuvers. This will also provide insight into the type of conflict scenarios that are not easily categorized and what additional rules should be defined for dealing with these scenarios;
- Proposed methods for resolving symmetrical conflict scenarios should be further researched and verified;
- The critical time window, defined in this thesis as the time period leading up to loss of separation in a conflict in which the implicit maneuver coordination advice must be followed, should be further analyzed. Specifically, the gradient threshold down to which the time to loss of resolution space is included in the critical time window and additional safety margins should be quantified.

Appendix A

Categorization Algorithm

Confl_areas (**s**,**v**) ≡

[Return location of CPAs (x,y,z), corresponding conflict areas and number of conflict areas on current flight path and in the maneuver area.]

Categorize (**s**,**v**, CPAs (x,y,z), confl_areas)) ≡

If conflict_areas_on_fp = 0
    Null;

Else if conflict_areas_on_fp = 1
    Lateral IMC heading on tangent + margin;

Else
    For CPA1:N [for all CPAs belonging to conflict areas on flight path]
        If $CPA_x < FP_x$
            Left = 1;
        Else
            Right = 1;
        End if
    End for

    If left = 0 OR right = 0
        If **Confl_areas_connected** = 0
            If **Confl_area_blocking** = 0
                Cat. 1 ⇒ Lateral IMC, 1 by 1, tangent to closest conflict
            Else
                Cat. 4 ⇒ Vertical / speed / combination
            End if
        Else
            If **Confl_area_blocking** = 0
                Cat. 2 ⇒ Lateral IMC, tangent to combined conflict area
            Else

```
                Cat. 4
            End if
        End if
    Else
        If Confl_areas_connected = 0
            If Maneuver_possible = 1
                If Confl_area_blocking = 0
                    Cat. 3 ⇒ Possibly lateral IMC, alternative: speed / vertical / comb.
                Else
                    Cat. 4
                End if
            Else
                Cat. 4
            End if
        Else
            Cat. 4
        End if
    End if
End if
```

Functions Used:

Confl_areas_connected
Returns 1 if conflict areas touch or overlap and 0 otherwise.

Confl_area_blocking
Returns 1 if a conflict area touches or overlaps (+ margin) the conflict area that ownship is planned to maneuver away from on the side opposite of the CPA location. Otherwise this function returns 0.

Maneuver_possible
This function returns 1 if the planned maneuver is possible considering ownship maneuvering capabilities and implicit coordination epsilon policy. When the CPA of a conflict on opposing side is close to flight path and conflict area is close to ownship, a maneuver will not be possible. In such cases this function returns 0.

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