An investigation into multi-aircraft conflict resolution by the Modified Voltage Potential algorithm and the potential effects of weighting the pair-wise avoidance vectors

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by

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T. Kuperus
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Nomenclature

List of Abbreviations

$ASAS$	Airborne Separation Assurance Systems
ATM	Air Traffic Management
CD	Conflict Detection
$CD\&R$	Conflict Detection & Resolution
CPA	Closest Point of Approach
CR	Conflict Resolution
DEP	The domino effect parameter
DEV	Deviation
LoS	Loss of Separation
LP	Largest Priority
$MACC$	multi-aircraft Conflict
MVP	Modified Voltage Potential
$PASAS$	Predictive Airborne Separation Assurance Systems
POS	Position
PZ	Protected Zone
SP	Smallest Priority
VO	Velocity Obstacle
FL	Flight Level
TAS	True Airspeed

List of Symbols

Ω	Spawn Rate
θ	Conflict angle
C	Number of Conflcits
d	Distance
k	Extra distance searched
N	Number of instantaneous aircraft
n_{int}	Number of intruders
r_{PZ}	Radius Protected Zone
t	Time

v	Velocity
w	Weight
A	Area
T	Time

I

Scientific Paper

An investigation into multi-aircraft conflict resolution by the modified voltage potential algorithm and the potential effects of weighting the pair-wise avoidance vectors

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***Abstract*—Increased air traffic activity has caused strain on current air traffic management systems. Through decentralization of air traffic control, this strain can be released and airspace capacity, safety and flight efficiency can be increased. The Modified Voltage Potential is a decentralized conflict detection and resolution method based on a force field analogy. Once a conflict has been detected, repelling velocity vectors are determined on board of the involved aircraft to find a conflict-free trajectory. The Modified Voltage Potential has proven to be effective and efficient in various studies, although unintentional behavior is shown when an aircraft has a conflicting trajectory with multiple aircraft at the same time. In these multi-aircraft conflicts, the suggested solution is found by summing the pair-wise resolution vectors. When a left hand-sided maneuver is suggested to solve one conflict, but a right hand-side maneuver is suggested to solve a second conflict, the summed solution does not result in a conflict-free trajectory. On the other hand, when both conflicts are solved by an equal left hand sided maneuver, the sum will suggest a maneuver twice the required size. Unintentional behavior is currently mitigated by recursive conflict resolution. This paper investigates if further improvements can be made by weighting the pair-wise resolution vectors. The effects of weights on conflict resolution mechanics are investigated through a series of multi-aircraft conflict situations. By means of free flight simulation, it is shown that weights can improve airspace stability, flight efficiency, and stability in a high-density free-flight environment.**

***Index Terms*—Free Flight, Conflict Resolution, Modified Voltage Potential (MVP), multi-aircraft conflicts, Airborne Separation Assistance System (ASAS), self-separation**

I. Introduction

The last decades have seen a strong increase in air traffic [1], the higher number of routes flown and the higher frequency of flights result in a growing strain on the air traffic management (ATM) system. The consequences are delays and increased flight distance, which results in increased cost and pollution.

Increased awareness of route efficiencies has driven research in the area of free flight, a concept where direct routes between origin and destination are flown rather than predefined paths over deviating way points. Although, this comes with challenges as the routes are currently predefined by air traffic controllers to create a clear and manageable overview of the airspace, necessary to separate traffic and to ensure safety. One way to ensure safety while offering possibilities of direct routing is by decentralizing air traffic control [2], [3] [4]. The on-board organisation of safe separation from other aircraft, without interference of a centralized organization, is called self-separation. The pilots are assisted in bearing this heavy responsibility by the Airborne Separation Assistance System (ASAS), which detects conflicting trajectories and suggests maneuvers to prevent loss of separation (LoS). Research in the area of self-separation focuses mainly on three elements, conflict detection (CD), conflict resolution (CR), and conflict prevention (CP)

Modified Voltage Potential (MVP) is a conflict detection and resolution algorithm developed by Hoekstra [5], from the ideas of a voltage based conflict detection and resolution method by Eby [6]. MVP ensures safe separation by tactical and implicitly coordinated maneuvers. Pair-wise conflict resolution vectors are calculated based on the principle of charged particles which repel and keep separated in that way. This relatively straight forward algorithm is well thought out for conflicts involving two aircraft. When more aircraft are involved in the conflict, the pair-wise resolution vectors are simply summed, as with the repelling forces acting on charged particles. For conflict resolution this does not always make sense. For instance, two equal pair-wise resolutions suggesting a 5 m/s velocity change would result in a summed velocity change of 10 m/s. Intuitively, this results in a larger velocity change than required. Moreover, when two conflicts would be solved by exact opposite velocity changes, the sum is zero and no movement is made, resulting in a potentially dangerous situation. Despite these seemingly poor characteristics, the MVP is often found as the best performing CR method in simulations of free flight airspace [7], [8], [9].

The research presented in this paper elaborates on the mitigation of inefficiencies and safety risks by iterative and cooperative conflict resolution in multi-aircraft conflicts using

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the MVP algorithm. The effects of weighting the pair-wise resolution vectors by various methods are investigated on a microscopic and macroscopic scale. It is shown that weighting pair-wise resolution vectors can decrease multi-aircraft conflict complexity as a result of emerging behaviour at high traffic densities, further improving both safety and flight efficiency.

II. Modified Voltage Potential

The Modified Voltage Potential (MVP) is a conflict detection and resolution (CDR) algorithm, which detects conflicts and calculates the corresponding resolution vector. MVP has the capability for both horizontal and vertical CDR, although this research is limited to horizontal flight and horizontal separation. MVP only uses information received through an Automatic Dependent Surveillance-Broadcast (ADS-B) system, as part of a distributed-dependent surveillance system for the CDR. The MVP is an on-board CDR algorithm and evaluates a conflict from the perspective of one aircraft, called the ownship, the other aircraft involved is called the intruder. Unless stated otherwise, the CDR mechanics will be evaluated from the perspective of the ownship in this research. This section will first elaborate on the three phases in MVP, conflict detection, conflict resolution and recovery. Then the solution space diagram is discussed as a framework to analyse instantaneous solutions as well as its discrepancies with respect to dynamic solutions.

A. Conflict Detection

The conflict detection (CD) module detects future violations of the separation minima by nominal propagation of aircraft state data received through ADS-B. In Fig. 1, a conflict between the ownship with velocity ($\mathbf{V_{own}}$) and an intruder with velocity ($\mathbf{V}_{int}$) is illustrated. The relative trajectory for the ownship with respect to the intruder is found by propagating the relative velocity ($\mathbf{V}_{rel}$). When the predicted distance at the closest point of approach ($|\mathbf{d}_{CPA}|$) is smaller than the separation minima, a loss of separation (LoS) is predicted. In the figure this is intuitively illustrated as the closest point of approach (CPA) is inside the protected zone (PZ). The horizontal protected zone is a circular area around the aircraft with a radius (r_{PZ}) equal to the horizontal separation minima (d_{sep}) of 5 NM [10]. Conflict detection is limited to a 300 second look-ahead time, which means that the ownship is in conflict with all intruders for which a future LoS is predicted at a time to LoS (t_{LoS}) smaller than 300 seconds.

When approaching this situation from the perspective of the intruder, identical time to LoS and time to CPA will be found due to the rotational symmetry.

B. Conflict Resolution

The conflict resolution (CR) module calculates the required velocity change or resolution vector $\Delta\mathbf{V}_{MVP}$ to prevent a LoS. The resolution vector acts in the direction of $\mathbf{d}_{CPA}$ and moves the CPA to the PZ border, which means that ownship grazes the PZ of the intruder. In other words, it ensures a path deviation which equals the difference between the separation

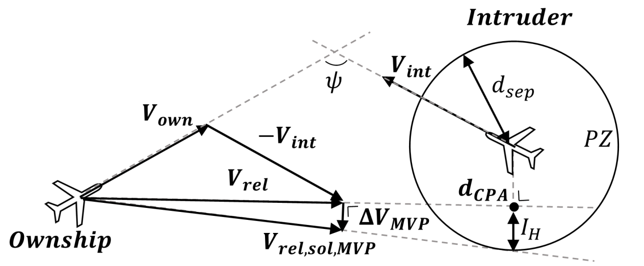


Figure 1. Conflict resolution using the MVP algorithm. The solution is shown from the perspective of the ownship.

minima and the predicted distance to CPA, the horizontal intrusion distance (I_H), at the time of CPA (t_{CPA}). The required velocity change is calculated using Eq. (1) and added to the current velocity vector to find the solution ($\mathbf{V}_{sol,MVP}$). In Fig. 1 the relative velocity resulting from this resolution vector ($\mathbf{V}_{rel,sol}$) shows that the ownship will indeed graze the intruders protected zone.

$$\Delta\mathbf{V}_{MVP} = \frac{I_H}{t_{CPA}} \cdot \frac{\mathbf{d}_{CPA}}{|\mathbf{d}_{CPA}|} \tag{1}$$

Due to the rotational symmetry of the conflict, $\mathbf{d}_{CPA}$ will be equal but opposite from the perspective of the intruder, while the horizontal intrusion and time to CPA are equal. This results in an exact opposite resolution vector. Therefore, the resolution is implicitly coordinated and no explicit line of communication is needed to coordinate the conflict resolution in cooperative conflict resolution.

When the ownship is in conflict with multiple intruders at once, the situation is called a multi-aircraft conflict. The solution is found by adding the sum of the pair-wise resolution vectors to the initial velocity.

C. Recovery

After the aircraft have found conflict-free paths, the solution velocity is maintained until a recovery to the initial path can be made. In the classical MVP, both aircraft will hold the conflict-free trajectory until the CPA has been reached. In shallow angle conflicts, this leads to repetitive conflicts. Aircraft conflicted again after the start of the recovery, resulting in longer conflict duration and LoS in some cases, [11], [8]. Where conflict duration is defined as the time between conflict detection and the start of the recovery. A new recovery method was developed by Schaberg [12], which aims at finding the point where the aircraft reverts to its desired trajectory to ensure it remains a conflict-free situation. Two criteria are used to determine this free to revert (FTR) point, the method is therefore called the "two criteria recovery method". The first criterion is met when the desired velocity is conflict-free, given that the intruder maintains its current velocity. The second criterion is aimed at preventing repetitive conflicts when both aircraft would revert back to the intended route at the same time. Since MVP relies on ADS-B data and implicit coordination, the intended route is unknown. Therefore, it is assumed that the intruder was flying the intended velocity at the start of the conflict and will revert back to this velocity at the end of the conflict. The initial velocity of the intruder as received by the ownship can deviate from the actual intended velocity when the intruder has already performed a conflict resolution maneuver for a previous conflict. This might cause the recovery start too soon or too late and could cause repetitive conflicts or larger deviations and conflict duration than required.

Schaberg [12] has shown that the two criterion method reduces the conflict duration for conflicts with conflict angles, denoted by $d\psi$ in Fig. 1, of 90 and 180 degrees. The conflict duration of a 15 degree shallow angle conflict increased to prevent repetitive conflicts. Additionally, an increased performance in terms of safety, efficiency, and stability was shown by simulating air traffic in free flight at low densities.

D. *Instantaneous Conflict Analysis vs Dynamic solution*

MVP approaches conflict resolution as a static situation at the moment of conflict detection. The calculated resolution vector solves the conflict when directly applied to the initial velocity. This implies an adaptation of the new velocity at the same position. While in reality, adopting a new velocity will take a certain time, during which the position changes.

The airspace is a dynamic environment, where new conflicts can arise at any time. Therefore, the surrounding area is scanned for new conflicts every second, and new resolution vectors are calculated if required. The dynamic behaviour of all aircraft implies that the resolution vectors change each iteration and that the final solution might deviate from the initial solution. Nevertheless, instantaneous conflict analysis from the conflict start provides useful insights in conflict resolution mechanics. Moreover, the dynamic solution is no more than a sequence of instantaneous solutions. This section introduces the solution space diagram (SSD) to evaluate static cases and elaborates on dynamic conflict resolution mechanics.

1) Instantaneous solution analysis: The instantaneous resolution of conflicts can be evaluated in more detail by using velocity obstacles [13], [14] combined with the minimum and maximum velocity to form the SSD [15]. The SSD shows which set of the reachable velocities will and will not result in a LoS. The SSD of the conflict in Fig. 1 is shown in Fig. 2. A conflict-free trajectory is found when the velocity of the ownship is outside the velocity obstacle, grazing solutions are found at the border of the velocity obstacle. The black dot illustrates that the MVP resolution vector finds a grazing solution.

Schaberg [12] used the SSD to study path deviations and conflict angles for different solutions. Where the path deviation is defined as the distance between the position of the aircraft after the conflict is solved and the expected position of the aircraft at the same time in case of no conflict resolution. By analyzing solutions inside the SSD, it was shown that conflict duration behaves linear for resolution vectors along the direction of the relative velocity and will asymptotically go to infinity near the velocity obstacle apex. At that point,

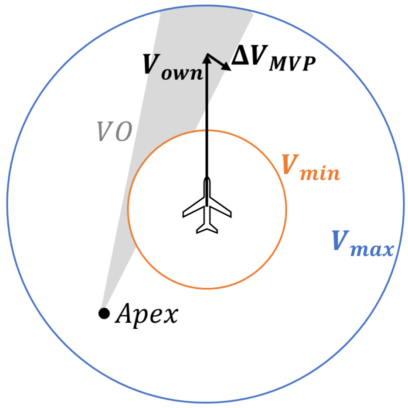


Figure 2. The SSD of Fig. 1. The orange and blue circle are the minimum and maximum velocity, respectively. The white space between both circles represent the set of available velocities, in grey the velocity obstacle representing the velocities conflicting with the intruder.

the relative velocity is zero and the aircraft follow parallel paths. Additionally, it was shown that the path deviation is only determined by the direction of the resolution vector (ϕ) and the intrusion, Eq. (2).

$$DEV = \frac{I_H}{sin\phi} \tag{2}$$

Minimum path deviation is reached when the resolution vector is perpendicular to the relative velocity, while the largest path deviations are reached when the resolution vector is in the direction of the apex. The minimum path deviation is equal to the horizontal intrusion when the conflict is solved one sided or half the intrusion when solved cooperatively. Interestingly, the linear behavior of the conflict duration prevents a larger resolution vector from resulting in a larger path deviation (DEV), as shown in Fig. 3. A larger maneuver does, however, result in an increased extra distance flown to solve the conflict.

Both deviation and conflict duration go to infinity when the solution is found near the apex. In pair-wise conflicts, the MVP solution will not be near this region, although in a multi-aircraft conflict situation the summed resolution vector might be closer to the apex. The velocity obstacle apex is therefore a location of interest in this research and will be used to find poorly solved situations. In addition to the resolution vector location, the size and direction of resolution vectors on the SSD will be used to get insights into resolution inefficiencies.

2) Dynamic solution: Every second, the pair-wise resolution vectors are recalculated and executed immediately. This implies that the execution of resolution vectors is limited by the aircraft dynamics when the suggested maneuver is larger than the maximum maneuver possible in a one second time span. At the start of the next iteration, the conflict might not be solved, although the recalculated solution will deviate from the instantaneous solution as the conflict geometry has changed. The dynamic solution therefore deviates from the instantaneous solution.

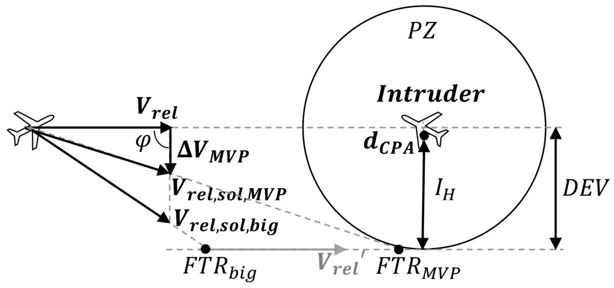


Figure 3. Recovery after conflict resolution using the two criteria method. The path deviation is dependent on the direction of the solution ϕ but independent from the magnitude of the solution.

This is beneficial in cooperative conflict resolution. When both aircraft would fully perform the instantaneous resolution vector, the required resolution is performed twice. Although, if the conflicts are solved dynamically, the solution will be smaller than the instantaneous solution, due to the repetitive reevaluation of the situation in combination with the cooperative solution. The conflict resolution by the ownship moves the velocity vector to the velocity obstacle border, while the conflict resolution of the intruder moves the velocity obstacle border to the velocity vector. Due to this cooperative resolution, the suggested solution with respect to the initial velocity shrinks every iteration. Therefore, the combined maneuver of the ownship and the intruder is not twice the instantaneous resolution, but the instantaneous solution plus the extra maneuver resulting from the last iteration. This small extra maneuver can be seen as a margin and is beneficial in crowded airspace.

III. Multi-Aircraft Conflicts

When the ownship is in conflict with multiple intruders at the same time, it is in a multi-aircraft conflict (MACC). The resolution vector is found by summing the pair-wise resolution vectors and will neither be perpendicular to all relative velocities if those are not exactly the same, nor is it likely that it suggests a grazing solution for both conflicts. Therefore, an inefficiency of the conflict resolution exists with respect to pair-wise conflicts resolution. Additionally, in some cases, the instantaneous solution does not find a conflict-free trajectory and the conflicts rely on the dynamic solution.

This section will first distinguish two types of MACC situations based on MACC geometries. Then, the conflict resolution mechanics of both types will be analysed and the potential positive and negative effect of the pair-wise conflicts on conflict resolution will be discussed.

A. Multi-Aircraft Conflict Geometries

When an aircraft is in conflict with multiple intruders at once and has therefore multiple resolution vectors, the situation is considered as a multi-aircraft conflict. A MACC is therefore mostly approached from the perspective of the ownship. If one of the intruders would also be in conflict

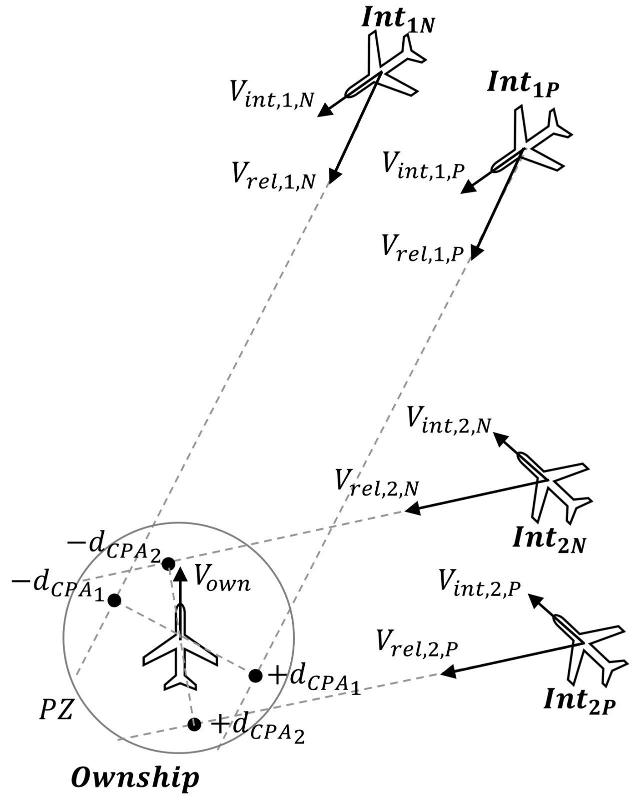


Figure 4. The pair-wise conflicts between the ownship and intruder one and the ownship and intruder two with both either a positive or negative $\mathbf{d}_{CPA}$, together form 4 multi-aircraft conflicts. Intruder one with $+\mathbf{d}_{CPA_1}$ is called Int_{1P}, and Intruder one with $-\mathbf{d}_{CPA_1}$ is called Int_{1N}. Intruder two holds the same name convention. Intruder one and two are in none of the cases in conflict with each other.

with another aircraft, this situation would be considered as a different MACC.

When composing a MACC by combining two pair-wise conflicts, with either positive or negative $\mathbf{d}_{CPA}$, four multi-aircraft conflict geometries exist, as shown in Fig. 4. In this figure, the relative velocities and relative paths are drawn from the perspective of the intruders rather than the perspective of the ownship. This provides a more direct overview of the CPAs of each conflict with respect to the ownship and the maneuver which solves the conflict. When the CPA is on the left hand side of the ownship, a maneuver to the right or clockwise heading change solves the conflict. A CPA on the right hand side is solved with a maneuver to the left or counterclockwise heading change.

The four MACC situations can be divided into two categories depending on the direction of the resolution vectors. When the resolution vectors suggest turns to different sides, i.e. one resolution vector suggest a turn to the left and the other suggests a turn to the right, the unweighted solution will not find an instantaneous solution and is therefore called *under-solved*. When both resolution vectors suggest a turn to the same side, the unweighted solution will find an instantaneous

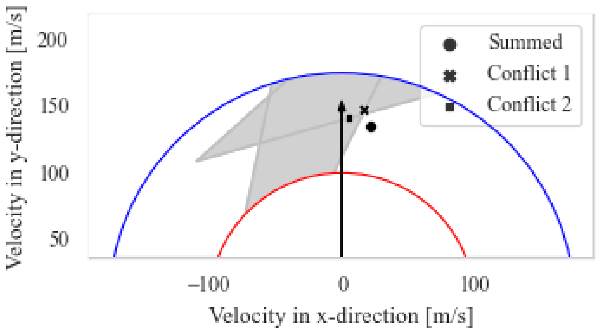


Figure 5. SSD of the ownship and intruders Int_{1P} and Int_{2P} as in Fig. 4. The red and blue line represent the minimum and maximum velocity, respectively. In grey the velocity obstacle representing the velocities conflicting with the intruder. The black arrow represents the current velocity of the ownship. The pair-wise resolution suggest heading changes in to the same side, resulting in a resolution vector beyond the border of the SSD. The instantaneous solution is oversolved.

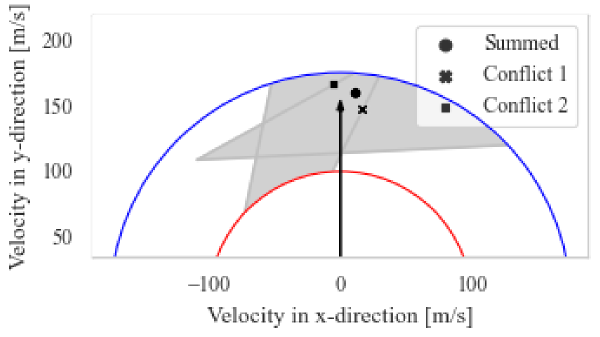


Figure 6. SSD of the ownship and intruders Int_{1N} and Int_{2P} as in Fig. 4. The red and blue line represent the minimum and maximum velocity, respectively. In grey the velocity obstacle representing the velocities conflicting with the intruder. The black arrow represents the current velocity of the ownship. The pair-wise resolution vectors suggest heading changes to different sides, resulting in a summed resolution vector inside the SSD, The instantaneous solution is undersolved.

solution which is larger than necessary and is therefore called *oversolved*.

B. Oversolved Multi-Aircraft Conflict

The conflict between the ownship and Int_{1P} as well as the conflict between the ownship and Int_{2P} both have a $\mathbf{d}_{CPA}$ on the right hand side of the ownship and therefore require a maneuver to the left to solve the conflict. Since both conflicts require a maneuver to the same side, the MACC is oversolved. Also the MACC between the ownship and intruders Int_{1N} and Int_{2N} is oversolved as both pair wise conflicts suggest a resolution maneuver to the left.

In Fig. 5 the SSD of the MACC between the ownship and intruders Int_{1P} and Int_{2P} is shown as well as the pair-wise and summed resolution vectors. The combined conflicts form the summed resolution vector and suggest a solution far outside the SSD. When the ownship executes this solution, the maneuver is larger than necessary, hence the name oversolved. As discussed, a resolution larger than necessary can decrease the conflict duration, but results in a larger distance flown. Additionally, the summed resolution vector is not perpendicular to any of the relative velocities, which drives a larger deviation compared to pair-wise conflicts.

1) Dynamic conflict resolution mechanics of oversolved multi-aircraft conflicts: Since the CDR system used in this research evaluates the conflicts every second, the magnitude of the overshoot is determined by the last conflict resolution iteration rather than the instantaneous solution, similar to two-aircraft conflicts. The difference is that the magnitude of the extra maneuver is not only determined by the last iterations, but also by the sum of both resolution vectors. The overshoot in the iterative solved conflict is therefore larger than that of each of the pair-wise conflicts separately, but smaller than the instantaneous solution.

It should be noted that overshoot only occurs when a conflict-free path is found for multiple conflicts at the same iteration. When one conflict requires a larger deviation than the other at the start of the MACC, the conflicts are likely to be solved sequentially. In that case, the MACC geometry initially suggests oversolving, but the last calculated resolution vector will be that of one conflict rather than the sum of both, therefore no overshoot will occur. In those cases, the final solution will be closer to the optimum solution of the last solved conflict, as this conflict is solved without interference of the other conflict in the last phase.

C. Undersolved Multi-Aircraft Conflicts

When the sign of $\mathbf{d}_{CPA}$ changes, the resolution vector also changes sign. Therefore, if the sign of $\mathbf{d}_{CPA}$ of one of the conflicts in an oversolved situation changes, the pair wise conflicts suggest opposite resolution maneuvers and the situation becomes undersolved. The situation where the ownship is in conflict with Int_{1N} and Int_{2P} or with Int_{1P} and Int_{2N} are undersolved.

In Fig. 6 the SSD of the MACC between the ownship and intruders Int_{1N} and Int_{2P} is shown as well as the pair-wise and summed resolution vectors. The summed resolution vector suggests a maneuver inside the SSD. The instantaneous resolution will not find a conflict-free path, hence it is called undersolved.

1) Dynamic conflict resolution mechanics of undersolved multi-aircraft conflicts: In an undersolved MACC, the aircraft rely on iterations to find a conflict-free path. Each iteration the trajectories are pushed further apart until a conflict-free path is found for all aircraft. The resolution mechanics depend on the geometry of the pair-wise conflicts.

When the resolution vectors for both intruders are exactly opposite, the sum is zero and the ownship does not make a resolution maneuver. The conflicts are solved by the one-sided solution of the intruders. Both intruders find a grazing solution and the deviation from their path is equal to the intrusion.

In most cases, like in Fig. 6, the resolution vectors are not exactly opposite. Therefore, the ownship will make a maneuver to solve one conflict. Although, this maneuver will counteract the resolution maneuver of the intruder in the other conflict. The direction of the summed resolution vector determines to what extend the ownship will contribute to one solution or counteract the other solution, as the angle between the relative velocity and the resolution vector drives the deviation. Since the relative velocities are unequal, the positive or negative contribution to the pair-wise conflicts is unequal as well. The positive contribution of the ownship reduces the required deviation by the intruder with respect to the one-sided solution. While the negative contribution of the ownship increased the required deviation by the other intruder. The summed deviation of all aircraft increases by the negative contribution made by the ownship. It should be noted that through the dynamic resolution the direction of the summed resolution vector changes per iteration. Therefore, the final resolution vector will not be along the direction of the initial resolution vector and the contribution of the ownship per conflict will be determined by the final solution rather than the initial solution.

Although a maneuver by the ownship increases the total deviation, it can decrease the time needed to find a conflict-free path by all aircraft and may therefore be beneficial in the resolution.

IV. Weighting Methods

MVP has shown some unintentional behavior in solving MACCs. The resolution vector of the ownship is often not in the optimal direction for both conflicts and it overshoots the grazing solution. In undersolved situations, the resolution efforts of the ownship benefit one conflict while counteracting resolution of the other conflict.

Although not all unintentional effects can fully be counteracted, weighting the pair-wise resolution vectors can affect the resolution mechanics and therefore benefit preferred characteristics. The weighted summation is shown in Eq. (3). In this equation, $\Delta\mathbf{V}_{MVP_i}$ is the resolution vector of conflict pair *i* with intruder *i*, w_i is the weight of that conflict and $\Delta\mathbf{V}_{MVP}$ is the summed resolution vector.

$$\Delta\mathbf{V}_{MVP} = \sum_i w_i \cdot \Delta\mathbf{V}_{MVP_i} \tag{3}$$

In this section, seven weights are developed, which show different advantages and disadvantages. Either to decrease the time to a conflict-free path, the deviation, conflict duration or overshoot. The mechanics of these weights are discussed at the end of this section.

A. Average

To decrease the size of the maneuvers of the ownship, the average of the vectors can be used rather than summing the pair-wise resolution vectors, to obtain the resolution vector of the ownship. This weighting method is conveniently called AVG. Each pair-wise conflict resolution vector is divided by the number of intruders n_{int} part of the MACC. Therefore, the weight of all conflicts is the same, as shown Eq. (4).

Table I
Overview of the weighting methods

Label	Description	Equation
AVG	Average	$w_i = \frac{1}{n_{int}}$
FAR	Moderate prioritization of larger d_i	$w_i = \frac{d_i}{d_{avg}}$
NEAR	Moderate prioritization small d_i	$w_i = \frac{d_{avg}}{d_i}$
LATER	Moderate prioritization of larger t_{LOS_i}	$w_i = \frac{t_{LOS_i}}{t_{LOS_{avg}}}$
SOON	Moderate prioritization of small t_{LOS_i}	$w_i = \frac{t_{LOS_{avg}}}{t_{LOS_i}}$
SEVERE	Full prioritization of the largest dv	$w_i = 1$ or $w_i = 0$
LIGHT	Full prioritization of the smallest dv	$w_i = 1$ or $w_i = 0$

$$w = \frac{1}{n_{int}} \tag{4}$$

The average absolute avoidance vectors will act in the same direction as the unweighted avoidance vector, albeit with a smaller size.

B. Moderate Prioritization on Distance or Time

Intruders closer to the ownship in distance or time to LoS can be seen as more urgent, compared to intruders with the same conflict angles but further away. MVP implicitly prioritizes more urgent conflicts as those require larger resolution vectors. By explicit prioritization of the more urgent conflicts in undersolved situations, the resolution per conflict will become balanced. Prioritizing less urgent conflicts results in larger differences, although this penalty is smaller. The difference between the distance or time based weights is driven by the conflict angles and therefore by the relative velocity. At small conflict angles, the ownship and intruder can be close together, while having a small relative velocity, the time to LoS is large in that case.

Weighting methods NEAR and FAR prioritize conflicts based on the difference between the ownship and the intruders. FAR prioritizes intruders further away over conflicts closer by, hence it prioritizes less urgent conflicts. The weight of intruder *i* is composed by dividing the distance between the ownship and intruder *i* over the average distance between the ownship and all intruders involved in the MACC, Eq. (5). The inverse of Eq. (5) will prioritize the conflicts with the smallest distance. This weight is called NEAR and is calculated using Eq. (6).

$$w_i = \frac{d_i}{d_{avg}} \tag{5}$$

$$w_i = \frac{d_{avg}}{d_i} \tag{6}$$

The same analogy holds for the time to LoS weights. The weighting method for prioritizing conflicts with the largest t_{LoS} is called LATER and the weighting method for prioritizing conflicts with the smallest t_{LoS} is called SOON. The weights are calculated using Eq. (7) and Eq. (8), respectively.

Table II
WEIGHTS FOR THE DISTANCE AND TIME WEIGHTS OF INTRUDER ONE AND TWO AS IN FIG. 4

	AVG	FAR	NEAR	SOON	LATER	LIGHT	SEVERE
w_1	0.5	1.3	0.8	1.1	0.9	0	1
w_2	0.5	0.7	1.4	0.9	1.1	1	0

$$w_i = \frac{t_{LOS_i}}{t_{LOS_{avg}}} \quad (7)$$

$$w_i = \frac{t_{LOS_{avg}}}{t_{LOS_i}} \quad (8)$$

C. Full Prioritization on Resolution Vector Size

More rigorous prioritization of one conflict over the others can be done by assigning a weight of one to one conflict and a weight of zero to all other conflicts. The methods LIGHT and SEVERE utilize this principle to prioritize the most or least urgent conflict based on the magnitude of the resolution vector. In a MACC involving two intruders this is straight forward. SEVERE assigns a weight one to the conflict with the largest resolution vector and a weight zero the other conflicts. LIGHT does the exact opposite. When more intruders are part of the MACC, two steps are taken. First, the resolution vectors which suggest a maneuver to the right and the resolution vectors which suggest a maneuver to the left are divided into two groups. The resolution vectors per group are summed. SEVERE assigns a weight of one to the largest pair-wise resolution vector in the group with the largest sum, and all other conflicts are assigned a weight of zero. LIGHT assigns the weight of one to the smallest resolution vector in the group with the smallest summed resolution vector, the other vectors are assigned a weight zero.

D. Resolution Mechanics of Weighting Methods

The mechanics of the weighting methods are explained further with the help of an oversolved and undersolved MACC situation as sketched in Fig. 5 and Fig. 6. The distance between the positive and negative intruders and the ownship is assumed to be equal for the simplicity of the example, $d_{O,1} = 72$ km, $d_{O,2} = 41$ km, the times to LoS are $t_{LoS,1} = 225$ seconds and $t_{LoS,2} = 275$ seconds. The weights are summarised in Table II.

The situations will be analysed using the instantaneous solutions shown in the SSD and in the description of the dynamic solutions. The weights prioritizing the more urgent conflicts, SEVERE, NEAR and SOON, are presented in red, orange and yellow, respectively. The weights prioritizing the less urgent conflicts, LIGHT, FAR and LATER are represented in blue, light blue, and green. MVP is represented in black and AVG in purple. The colors are grouped in coordination with the prioritization preference, to make the results more intuitive to read.

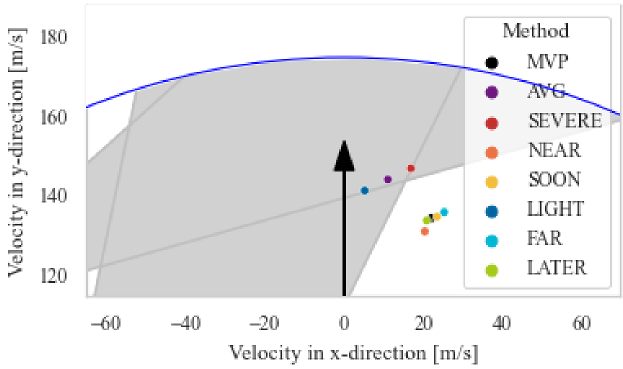


Figure 7. SSD with instantaneous solution of weighted vectors of the oversolved conflict with the ownship and intruders Int_{1P} and Int_{2P} as in Fig. 4

1) Resolution mechanics in oversolved multi-aircraft conflicts: The SSD of the oversolved situation is sketched in Fig. 7. The summed resolution vectors of MVP, NEAR, SOON, FAR, and LATER show similar results and are all still beyond the border of the SSD. Therefore, the direction and magnitude of the resolution vectors will be similar. The resolution vectors of SEVERE, AVG and LIGHT on the other hand are inside the SSD, due to the cooperative resolution, these methods will find a solution near the border and therefore decrease overshooting. It is however imaginable that this may cause a delay in the conflict resolution due to smaller velocity changes per iteration at the end of the solutions. The slower solution might result in a more sequential resolution. The benefit is that the direction of the resolution vector will be closer to the optimum solution of the last solved conflict, while also solving the other conflict. Therefore, the deviation is expected to decrease.

2) Resolution mechanics in undersolved multi-aircraft conflicts: The SSD for the undersolved situation is sketched in Fig. 8. AVG finds the smallest solution again, it is in the same direction as MVP although half the size. SOON and LATER show a similar result to MVP due to the small differences in time to LoS. NEAR and FAR, find the solution further from MVP due to larger differences in distance between the aircraft. Contrary to the oversolved cases, SEVERE and LIGHT show the most extreme solutions. The solutions are found at the edge of one velocity obstacle, although still inside the other velocity obstacle. Solving one conflict first will result in high sequentiality.

When interpreting MVP and AVG as weights without prioritizing one conflict over the other, or as neutral, the solutions can be divided in two groups. LIGHT, NEAR and LATER prioritize conflict one, while SEVERE, FAR and SOON prioritize conflict two. It stands out that NEAR finds a solution in favor of conflict one while SEVERE and SOON find a solution in favor of conflict two, while all attempt to prioritize the more urgent conflict based on different interpretations of urgency.

As discussed, the average deviation is decreased when the

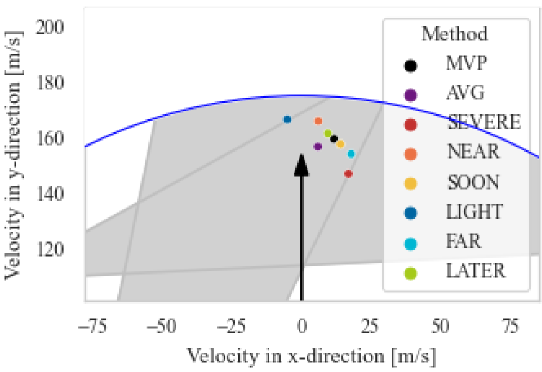


Figure 8. SSD with instantaneous solution of weighted vectors of the oversolved conflict with ownship and intruders Int_{1N} and Int_{2P} as in Fig. 4

relative velocity of both conflicts is not negatively affected by the ownship. Therefore, smaller resolution vectors are preferable, for similar pair-wise resolution vectors it is therefore beneficial to weight them equally as AVG and MVP do. When large differences exist, it is beneficial to adjust the weights correspondingly, larger resolution vectors should be assigned a lower weight and vice versa, as is done by LIGHT, FAR and LATER. On the other hand, prioritizing the conflict with the largest resolution vector, as done by SEVERE, NEAR and SOON, will decrease the time required to solve all conflicts.

V. Experiments

Conflict resolution performance of weighted and unweighted MVP methods are investigated in two series of experiments. In the first series, a set of MACC situations with varying geometries is solved, which gives insights into the conflict resolution mechanics and the strengths and weaknesses of the methods. In the second series of experiments, the behavior of the methods in a free flight environment is investigated. In those experiments the emergent behavior will be analysed and the performance on a macroscopic scale will be measured. Both experiments will be performed as fast time simulations.

This section will elaborate on the simulation environment used for the experiments, as well as the setup of both experiments and the expected results.

A. Simulation Environment

The fast-time simulations will be performed in the open source air traffic simulator Bluesky [16]. In Bluesky, aircraft dynamics are modeled using aircraft characteristics, dynamic and kinetic performance from the OpenAP library [17]. Bluesky is written in python code and accessible to extend with the developed weights as CDR methods. Additionally, MVP is already implemented and used in previous research [8], [18], [7] and [12]. It should however be noted that the simulations do not account for human behavior. All simulated aircraft are Boeing B747-400 models at FL100. The flight level is chosen such that there is a sufficient margin to increase or decrease the velocity during conflict resolution maneuvers. The performance limits are shown in Table III.

Table III
Performance limits Boeing B747-400 aircraft at FL100

Characteristic	Value
Speed	162-406 kts
Acceleration	0.5 m/s^2
Deceleration	-0.5 m/s^2
Turn rate	1.1 - 1.5$°s^{-1}$

B. Synthetic Multi-Aircraft Conflict Experiments

Conflict resolution mechanics of the weighted and unweighted methods are analysed for a series of MACC geometries, where the ownship is in conflict with two intruders. The simplicity of two conflicts ensures a better understanding of the mechanics, while a variation of the pair-wise conflict geometries will expose the characteristics of the methods. The geometry will vary based on the conflict angle and the time to LoS per conflict.

By varying the conflict angles, the position of that intruder will change and the differences between time and distance weights will be shown well. Additionally, the direction of the resolution vector will change. Because smaller or larger time to LoS mostly effects the size of a maneuver and will not have impact on the kind of maneuver, the time to LoS is varied as a difference between both conflicts rather than independent per conflict. The maximum difference in magnitude of the resolution vectors is further enlarged by assigning different sized absolute distances to CPA to each conflict. The conflict angle on the other hand is varied independently per conflict as also the location of the apex per conflict plays a role, therefore variation in relative difference per conflict angle is insufficient.

All Boeing B747-400 in those experiments will have an an initial ground speed of 300 kts at FL100, such that there is a sufficient margin for maneuvers within the performance limits as shown in Table III.

1) Scenario generation: The locations and headings of the intruders relative to the ownship are determined by varying time to LoS, and conflict angle, but constant absolute distance to CPA.

As discussed, the time to LoS of both intruders are defined to adhere to the specified differences between both conflicts. The difference in time to LoS is determined by $\Delta t_{LoS} = t_{LoS_1} - t_{LoS_2}$.

For each Δt_{LoS} a set of MACCs is created by combining two pair-wise conflicts with conflict angles between -180 and 180 degrees. Based on the conflict angles and the difference in time to LoS only, each situation finds a mirrored version around the heading of the ownship. The situation where $d\psi_1 = x_1$ and $d\psi_2 = x_2$ finds a mirrored version in the situation where $d\psi_1 = -x_1$ and $d\psi_2 = -x_2$. This provides the opportunity to cover two of the four possible conflict

Table IV
CONFLICT DESIGN PARAMETERS GRID EXPERIMENTS

	Step	**Set 1**	**Set 2**
$d_{CPA_1}[NM]$	-	4.5	4.5
$d_{CPA_2}[NM]$	-	2.5	2.5
$\Delta t_{LoS}[s]$	50	[-200,0]	[50,200]
$t_{LoS_1}[s]$	50	[75,275]	275
$t_{LoS_2}[s]$	50	275	[75,225]

geometries as illustrated by Fig. 4, for a given combination of angle and difference in time to LoS. Therefore, oversolved and undersolved situations are covered in two different sets.

The MACC situations for predefined independent variables are created offline before being simulated in Bluesky. All aircraft are assigned a heading, velocity, and altitude at the origin, the destination is at 800 seconds from the origin.

2) Independent variables: To create the sets of undersolved and oversolved MACCs, the time to LoS, and conflict angle of both conflicts are varied. While the absolute distance to CPA of intruder one is 4.5 NM and that of intruder two is 2.5 NM. Each MACC situation will be solved by all conflict resolution methods as presented in Table II.

The time to LoS of the pair-wise conflicts range within the limits of a conflict. The maximum time to LoS is 275 seconds, just below the look ahead-time. The minimum time to LoS is 75 seconds, smaller times to LoS are not included, as those are not likely to occur in reality as resolution efforts are already made far in advance, and these conflicts are close to the TCAS region [19], where a different resolution is applied.

The independent variables are composed in a step-wise manner for all parameters, with discrete steps of 30 degrees for the conflict angles, and 50 seconds for the time to LoS. This corresponds to nine Δt_{LOS} steps, ranging from -200 to 200 seconds and 12 conflict angle steps ranging from -165 to 165 degrees or 15 to 345 degrees. This results in a total of $2 \cdot 12^2 \cdot 9 = 2,592$ MACC situations. All situations will be solved by all methods. The MACCs are divided in two sets where $\Delta t_{LOS} \leq 0$ or $\Delta t_{LOS} > 0$ and are summarised in Table IV. When Δt_{LoS} is positive, the closest aircraft has the highest intrusion and when Δt_{LoS} is negative, the closest aircraft has the smallest intrusion. Each set exists for both oversolved and undersolved conflict geometries that brings a total of four sets.

C. Dependent Measures of Multi-Aircraft Conflict Resolution

The performances of the conflict resolution methods per conflict design parameter are measured as the number of iterations needed to solve a conflict (n_{its}), the conflict duration (t_{conf}), and the deviation. The number of iterations and the conflict duration indicate how fast conflicts are solved. A slow solution can be disadvantageous in an environment with more traffic around, as the aircraft can potentially get in conflict with more other aircraft at the same time, resulting in multiple MACCs at the same time, which might be more difficult to solve. The conflict duration is measured as the time between conflict detection and the moment when the FTR point has been reached. Large conflict durations indicate inefficient solutions.

The deviation is defined as the distance between the position of the aircraft after the conflict is solved and the expected position of the aircraft at the same time in case of no conflict resolution, as shown in Fig. 3. The deviation is an important metric, as a large path deviation increases the distance flown. Additionally, a larger deviation leads to a larger possibility of new conflicts in a situation where more traffic is present.

D. Airspace Experiments

The emergent effects of the weighted and unweighted methods are evaluated in a fast-time simulation representing airspace in free flight. This section elaborates on the design of this experiment.

Traffic is simulated in a predefined experiment area, representing the airspace in free flight. The experiment area is defined as a square area with sides of 306 NM. In the experiment area, a free flight environment is simulated at predefined traffic densities where uniformly distributed aircraft are assigned a direct route which crosses the experiment area.

Around the experiment area, a simulation space is defined. The top of the simulation space is at FL100, the bottom border is at FL098, and the sides have a length 613 NM. Aircraft are simulated inside the simulation space, but only part of the experiment when they are inside the experiment area. Once the simulation space borders are crossed, the aircraft are deleted from the simulation. The area between the experiment area border and simulation has a low traffic density and serves as a spawning area for aircraft entering the simulation and a margin for aircraft briefly crossing the experiment area border due to conflict resolution. This simulation environment is modified from the experiments used in Sunil2017b and [9].

The ground speeds of the Boeing B747-400 aircraft at FL100 are uniformly distributed between 291 kts and 322 kts in these experiments. This provides a margin for maneuvers within the performance limits as shown in Table III.

1) Scenario generation: Uniformly distributed traffic is designed in two steps. First, the aircraft route origins are uniformly distributed at the experiment area border. Second, uniformly distributed headings are assigned, provided that the destination is inside the experiment area. The planned flight time is one hour, corresponding to an average flight distance of 306 NM. Therefore, the destinations are found close to the border of the experiment areas.

When an aircraft reaches the destination, it will descent and leave the simulation space. Due to conflict resolution maneuvers, it might happen that an aircraft passes the destination without descending, it is then redirected to a backup destination outside the simulation space. To reduce the likelihood that aircraft are in conflict when spawned, the spawning location is in the low density area between the experiment border and

Table V
TRAFFIC DENSITIES IN AIRSPACE SIMULATIONS

	Density $[AC/10,000NM^2]$	Instantaneous AC $[-]$
Low	20	187
Moderate	25	234
High	30	281

simulation border. It is located at two and a half times the look-ahead time to the route origin and it ensures that no heading change is required to fly the direct route.

The density in the simulation area is controlled by an equal aircraft spawning rate and aircraft deletion rate, assuming that the routes will be completed in the planned time. The flight time might however increase in simulations due to conflict resolution. Resulting in higher traffic densities. The spawn rate Ω is determined by multiplying the average planned flight time (t_{flight}) by the number of instantaneous aircraft in the experiment area to meet the desired traffic density (N), as shown in Eq. (9) [20].

$$\Omega = t_{flight} \cdot N \tag{9}$$

To ensure that the density is at the designed level when the measurements start, a density build-up period of 1.5 hours is included, before the experiments start. The experiment will have a duration of three hours, resulting in four and a half hour simulations. Validation of the experiment composition is shown in Appendix A.

2) Independent variables: The experiments include the conflict resolution methods and traffic density as independent variables. The methods developed in this study and presented in Table II are used as conflict resolution methods in the experiments, as well as the unweighted MVP. Additionally, simulations without conflict resolution method will be performed to verify the experiment design and serve as a baseline for stability measures. The performance will be measured in simulations with either low, medium or high densities as presented in Table V. The highest density is near the approximated en-route peak density of 32 aircraft per 10 000 NM^2 above the Netherlands [11].

The independent variables form $9{\cdot}3 = 27$ combinations. The airspace is simulated 15 times for each combination, resulting in a total of $27 \cdot 15 = 405$ simulations per method.

E. Dependent Measures of Airspace Simulations

The resolution performance of the conflict resolution method is measured in three categories of dependent variables. In this section, first the stability measures will be discussed, followed by efficiency measures and finally the safety measures.

1) Stability: The airspace stability refers to the number of extra conflicts induced by the resolution of an initial conflict. A resolution maneuver of the ownship can lead to a new conflict which would not have existed without the maneuver. When this destabilizing effect is too large, many aircraft get in conflict with each other, effecting the route efficiency and potentially the safety. Airspace stability can be quantified using the domino effect parameter (DEP). The DEP is the proportion of destabilizing conflicts. It is determined using the conflict count of a simulation without conflict resolution $C_{total_{nr}}$ and the conflict count of the same simulation with conflict resolution, $C_{total_{wr}}$, Eq. (10). The conflict counts only include unique pair-wise conflicts, repetitive conflicts are not included.

$$DEP = \frac{C_{total_{wr}}}{C_{total_{nr}}} - 1 \tag{10}$$

2) Efficiency: The efficiency is measured as the percentage extra distance flown d_{extra} between the distance flown in the experiment area d_{flown} and the direct distance from the location where the aircraft enters the experiment area to its destination d_{direct}, as shown in Eq. (11). The distance flown will be larger than the direct distance due to conflict resolution.

$$d_{extra} = 100 \cdot (\frac{d_{flown}}{d_{direct}} - 1) \tag{11}$$

3) Safety: The safety is measured based on the number of LoS per experiment and the severity of the LoS. The intrusion severity LoS_{sev} is the fraction of the protected zone radius which is violated at the closest distance between the two aircraft, it is calculated using Eq. (12). In this equation d_{CPA} is the actual closest point of approach rather than the predicted closest point of approach.

$$LoS_{sev} = \frac{d_{CPA}}{d_{sep}} - 1 \tag{12}$$

Additionally, the number of MACC involvements per aircraft and the number of iterations per aircraft per conflict involved in the MACC are measured. It should be noted that this also accounts for aircraft which are part of a MACC as intruders, but do not conflict with second aircraft themselves. Complex and poorly solved MACCs can lead to potentially dangerous situations.

F. Hypothesis

The expected effects of the weighted methods will be discussed per experiment, starting with synthetic MACC experiments and followed by the airspace experiments.

1) Hypothesis of synthetic MACC experiments: It is expected that undersolved MACC situations will be solved at a higher cost in terms of all dependent measures compared to the oversolved situations, due to the counteracting resolution of the pair-wise conflicts. Additionally, the cost of resolution for each metric is expected to increase with increasing positive Δt_{LoS}, as those situations require larger resolution maneuvers. Additionally, it is hypothesised that conflicts with smaller angles are solved less well than conflicts with higher angles. As the penalty for resolution vectors with a small deviation from the optimum solution is larger for conflicts with smaller conflict angles [12]. This is well illustrated by shallow angle conflicts, where the aircraft can result in parallel flight for deviating resolution maneuvers.

In oversolved cases, AVG, LIGHT and SEVERE are expected to cause larger conflict durations compared to MVP due to smaller resolution vectors and require a larger number of iterations due to smaller steps per iteration. The benefit of smaller and more focused time steps is expected to be seen in reduced deviation, due to the final solutions which are closer to the optimal direction of one of the pair-wise solutions. The other methods are expected to perform similar to MVP.

In undersolved cases, the average number of iterations will be the smallest if all conflicts are solved at the same time. As more urgent conflicts require more iterations to be solved than less urgent conflicts, prioritizing more urgent conflicts is expected to have an equalizing effect on the number of iterations per conflict. Accordingly, NEAR, SOON and SEVERE are expected to decrease the average number of iterations. The average deviation in undersolved cases decreases for decreasing deviation of the ownship. This will be achieved when the summed resolution vector is closer to zero, for similar but opposite resolution vectors AVG is therefore expected to reduce deviation, while prioritizing less urgent conflicts by LIGHT, FAR, and LATER is expected to reduce deviation at larger differences.

2) Hypothesis of airspace experiments: Since the weighting methods are specifically developed to only affect MACC resolution, it is expected that the effects are less pressing in the airspace experiments compared to the synthetic MACC experiments, as only a small part of the conflicts are involved in MACCs [12], [8]. The effects of weights in simulations are however expected to increase at higher densities as the number of MACCs increases with an increased density.

NEAR, SOON, and SEVERE prioritize more urgent conflicts, it is therefore hypothesised that those methods will result in less LoS and lower mean LoS severity. On the other hand, FAR, LATER, and LIGHT prioritize less urgent conflicts and are therefore expected to lead to an increased number of LoS and LoS severity.

The number of iterations required to solve a MACC are expected to decrease similarly in the airspace simulations as in the synthetic MACC experiments. Since the effects in undersolved cases are expected to be larger than the effects in oversolved cases, it is hypothesised that methods NEAR, SOON and SEVERE decrease the number of iterations required to solve a MACC compared to MVP, while AVG, LIGHT, FAR and LATER will increase the number of iterations.

A lower deviation per MACC is expected to reduce the distance flown per aircraft. A decrease distance flown is expected to result in a decrease number of conflicts and therefore a lower DEP. AVG is expected to reduce the deviation in most cases, it is therefore expected that AVG will show the largest decrease in distance flown and DEP. Since the effects of undersolved are expected to be larger than oversolved, LIGHT, FAR and LATER are expected to decrease the distance flown and DEP as well, although less than AVG as the decreased deviation is expected to be less consistent. SEVERE, NEAR and SOON are expected to show an increase in distance flown.

VI. RESULTS

In this section first the results of synthetic multi-aircraft conflicts experiments are presented, followed by the results of airspace experiments.

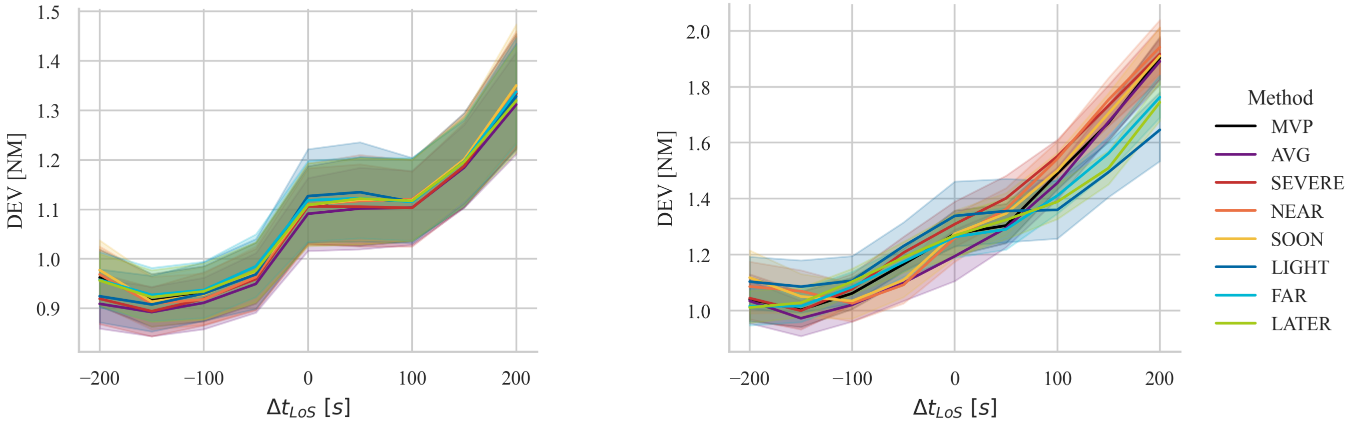
A. Results of Synthetic Multi-Aircraft Conflicts

The performance measures of synthetic MACCs are presented separately for the oversolved and undersolved cases as a function of the design parameters Δt_{LoS} and $|d\psi_i|$. Since Δt_{LoS} denotes a relationship between both intruders, the average results of both conflicts in a MACC are included, it represents the resolution performance of a MACC. As $|d\psi_i|$ only denotes the angle of one conflict, the results are grouped by pair-wise conflicts rather than per MACC. Due to the rotational symmetry of pair-wise conflicts, the results are presented per absolute conflict angle rather than positive and negative values. The results show the strengths and weaknesses of the methods per conflict rather than per MACC.

The results are presented as the mean with the 95 % confidence intervals per method. The significance of the results is investigated using Wilcoxon signed-rank tests, with the null hypothesis that the difference between the pairs follows a symmetric distribution around zero [21]. Differences between the results per method are deemed significant when $p \leq 0.05$. Since the unweighted method is compared to seven weighted methods per density, a Bonferroni correction was adjusted [22]. Therefore, the null hypothesis will be rejected and the difference between the results will be regarded significant when $p \leq 0.0071$. The results of the Wilxocon signed-rank tests are summarised in Appendix B, significant results will be discussed in this paper. Additional experiments for situations with other combinations of distance to CPA per conflict are presented in Appendix C.

The experiments are designed such that the ownship is in conflict with the intruders and the intruders can move freely. If during the conflict resolution the intruders are also in conflict with each other, the solution is affected and it is not possible to make a fair comparison to the other MACC situations. Therefore, a MACC is excluded from the results when the intruders are in conflict with each other.

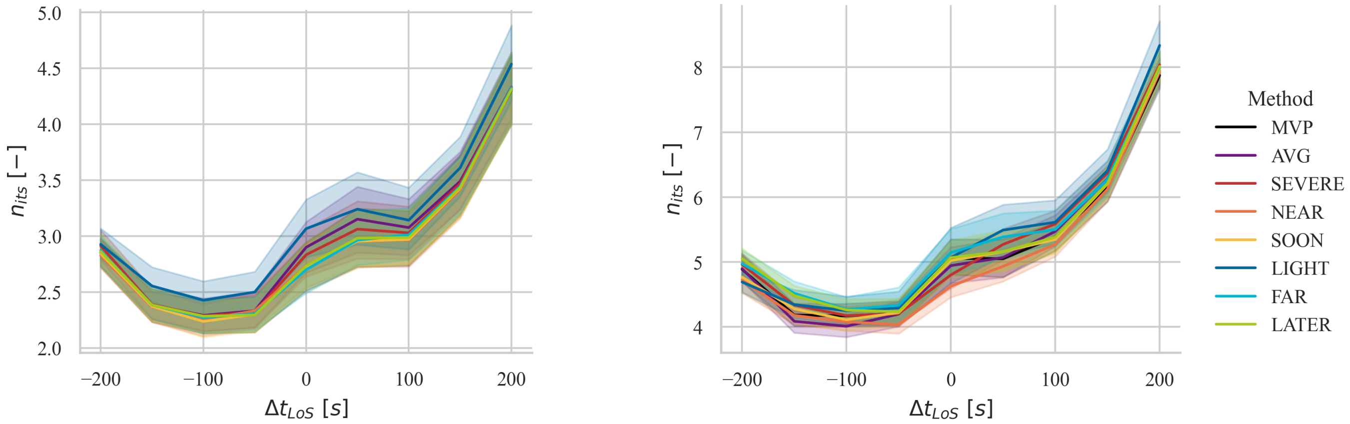
1) Difference in time to LoS: The effects of Δt_{LOS} on deviation, conflict duration, and number of iterations per aircraft per conflict are for each method presented in Fig. 9, Fig. 10 and Fig. 11, respectively. The oversolved cases show better performance compared to the undersolved cases. The deviation and number of iterations increase with increasing differences in time to LoS and are small where both resolution vectors have similar sizes. At lower Δt_{LOS} the measures increase again. A natural dependency between the conflict duration and t_{LOS} is seen, as the highest conflict duration is at $\Delta t_{LOS} = 0$ seconds, where both conflicts have the highest time to LoS at the start of the conflict.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

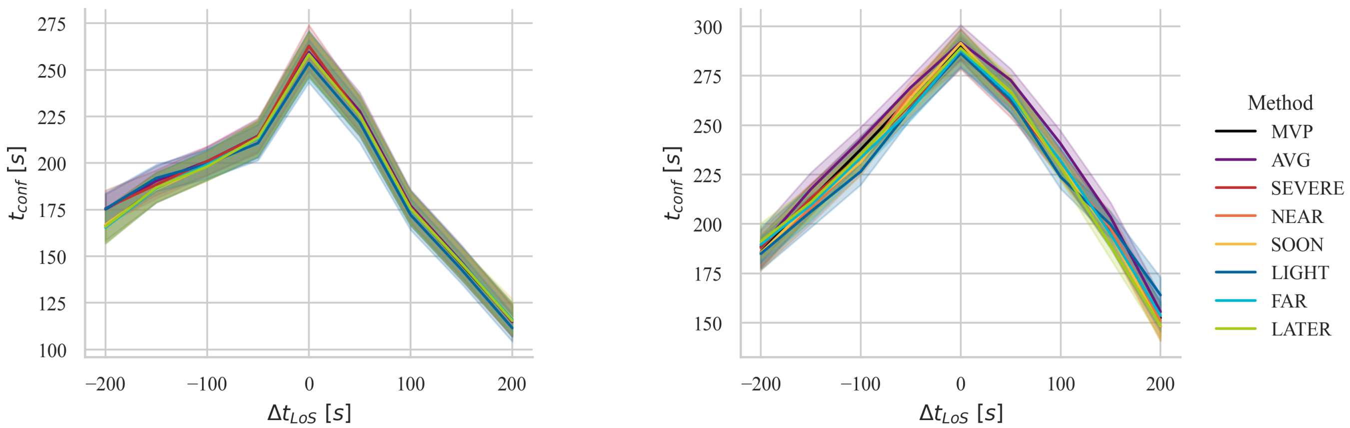
Figure 9. The effects of weighted methods on the average deviation as function of Δt_{LOS}. The lines represents the mean and the shading represents the 95% confidence intervals.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

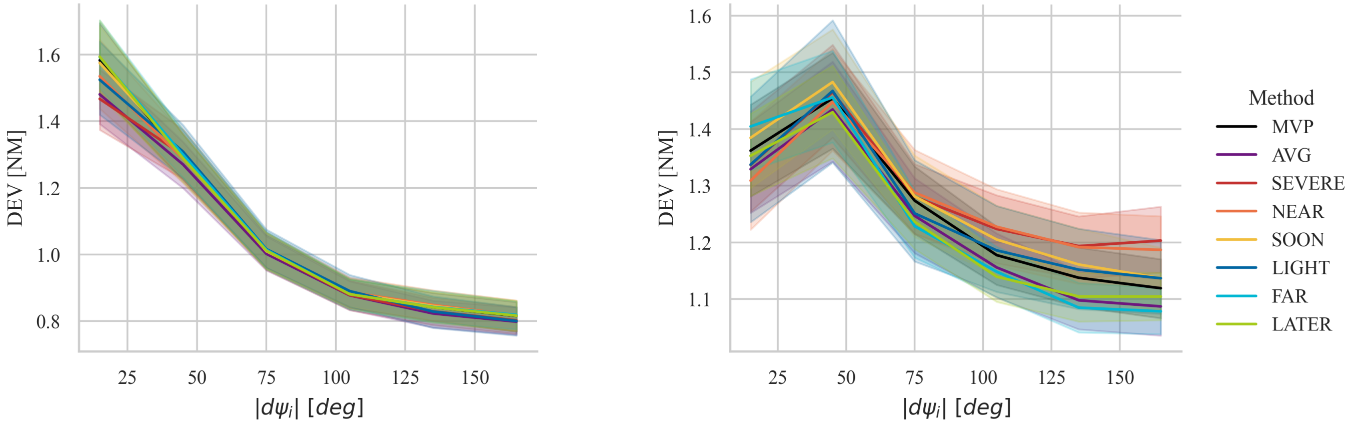
Figure 10. The effects of weighted methods on the average number of iterations per aircraft per conflict as function of Δt_{LoS}. The lines represents the mean and the shading represents the 95% confidence intervals.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

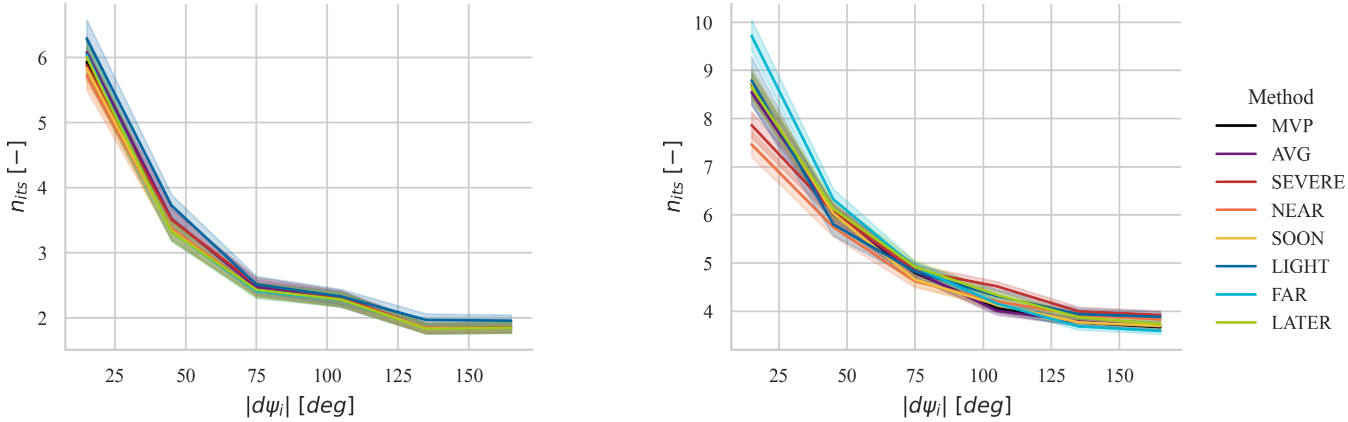
Figure 11. The effects of weighted methods on the average conflict duration as function of Δt_{LoS}. The lines represents the mean and the shading represents the 95% confidence intervals.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

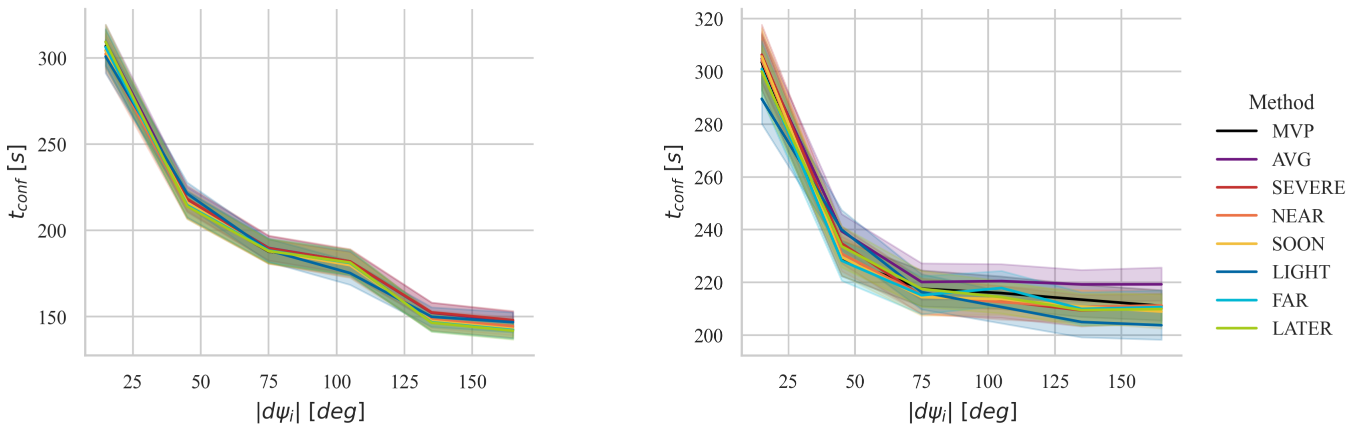
Figure 12. The effects of weighted methods on the average deviation as function of $|\Delta\psi|$. The lines represents the mean and the shading represents the 95% confidence intervals.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

Figure 13. The effects of weighted methods on the average number of iterations per aircraft per conflict as function of $|\Delta\psi|$. The lines represents the mean and the shading represents the 95% confidence intervals.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

Figure 14. The effects of weighted methods on the average conflict duration as function of $|\Delta\psi|$. The lines represents the mean and the shading represents the 95% confidence intervals.

In oversolved MACCs, all methods except LIGHT show similar performance compared to MVP for all conflict parameters. LIGHT shows an increase in number of iterations and deviation for all Δt_{LOS}, while decreasing the average conflict durations.

In undersolved MACCs, larger differences are seen. For positive Δt_{LOS} the methods prioritizing less urgent conflicts and especially LIGHT require a lower deviation to solve the MACC compared to MVP, while the methods prioritizing more urgent conflicts require larger deviations. AVG shows a decrease in deviation at negative Δt_{LOS}. Other methods show similar performance to MVP at negative Δt_{LOS}, where NEAR and SOON require slightly smaller deviation at situations between $\Delta t_{LOS} = -50$ and $\Delta t_{LOS} = -100$ seconds but larger deviation at smaller Δt_{LOS}.

Methods prioritizing more urgent conflicts outperform methods prioritizing less urgent conflicts in terms of the number of iterations required, where NEAR shows especially strong performance. It stands out that LIGHT shows weak performance at higher Δt_{LOS}, while other methods converge here.

The average conflict duration is highest for AVG at all Δt_{LOS}, while LIGHT shows a lower average conflict duration up to $\Delta t_{LOS} = 100$ seconds. The other methods show results similar to MVP.

2) Conflict angles: The effects of conflict angle on deviation, conflict duration, and number of iterations per aircraft per conflict are for each conflict resolution method presented in Fig. 12, Fig. 13 and Fig. 14, respectively. All dependent measures show higher values for smaller conflict angles, and decrease following a decreasing slope. Undersolved situations are solved at a higher cost than oversolved situations. An exception on both observations is found for the deviation in undersolved shallow angle conflicts.

It stands out that SEVERE and AVG show a large decrease in deviation in shallow angle conflicts in oversolved MACC situations. LIGHT shows a larger number of iterations, whilst the other methods show similar performance in these measures. Results in terms of conflict durations are similar.

Conflicts in undersolved MACC situations with higher conflict angles, SEVERE and NEAR cause a larger deviation than MVP, while other methods cause smaller deviations. In shallow angle conflicts NEAR shows a steep drop in deviation and perform best. SEVERE and NEAR also show large improvements in terms of the number of iterations at shallow angles, while LIGHT and FAR show poor performance. LIGHT does show good performance in terms of conflict duration at small and large angles. Other methods also show a decrease in average conflict duration compared to MVP. Except for AVG, which shows large conflict durations for all angles.

B. Results of Airspace Experiments

The results are presented in box-and-whisker plots, visualizing the sample distribution, grouped by method and density. The significance of these results are investigated using non-parametric tests. The Wilcoxon signed-rank test is used for the number of LoS per simulation, number of MACCs per flight, extra distance flown, and DEP, as those are measures of paired data. As the LOS severity and number of iteration required per MACC are measures of unpaired data, the Wilcoxon signed-rank test can not be used. Instead, the Mann-Whitney U test is used to investigate if there is a difference in medians [23]. The difference between the results will be regarded significant when $p \leq 0.0071$. An overview of all test results are presented in Appendix D and the significant results are shown in this paper.

1) Safety: In Fig. 15 the number of LoS per simulation is shown and in Fig. 16 the LoS severity is shown. The number of LoS and the average severity increase with increased traffic density. LIGHT, LATER and FAR, have more LoS and more severe LoS compared to MVP. The other methods show a similar number of LoS as MVP, where NEAR and SOON show a decrease in severity and therefore improve the safety ($p \leq 2.39E-04$, $p \leq 9.71E-04$).

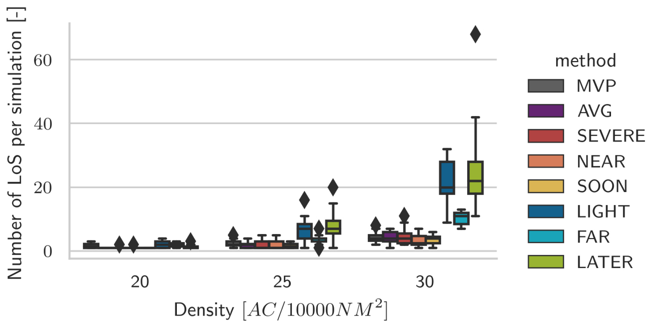


Figure 15. Number of LoS per experiment

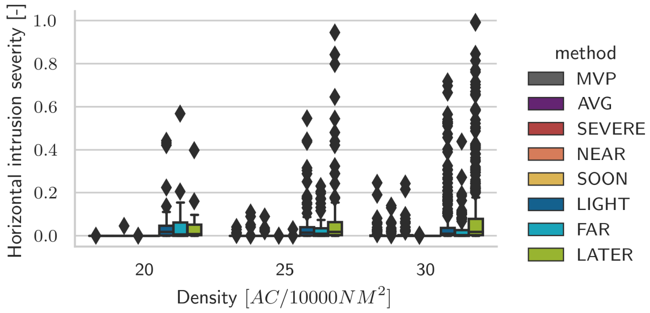


Figure 16. LoS severity per LoS

In Fig. 17 the average number of MACC involvements per flight per experiment is shown. The number of MACC involvements increases with an increased density. The largest differences are found at the highest density, where only LIGHT, NEAR and SOON resulted in a significant decrease ($p \leq 9.91E-04$, $p \leq 4.29E-06$, $p \leq 4.78E-04$).

The number of iterations per aircraft involved in a MACC is shown in Fig. 18. This figure illustrates an increase of number of iterations for an increased density. The only significant

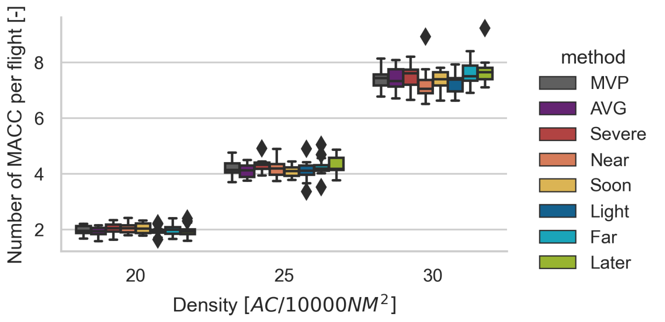


Figure 17. Average number of MACC involvements per flight per experiment

improvements found after the Wilcoxon tests are LIGHT, NEAR, and SOON ($p \leq 6.55E-03$, $p \leq 3.86E-03$, $p \leq 4.99E-06$).

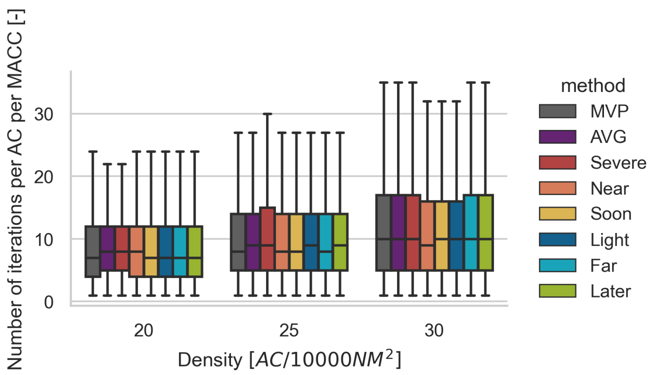


Figure 18. Number of iterations per aircraft involved in a MACC

2) Efficiency: An increased traffic density results in an increased distance flown, as shown in Fig. 19. This is a result of the extra number of conflicts per aircraft. The effects of the weighting methods on aircraft flight distance also become more significant at higher traffic densities, as a result of the higher number of involvements in MACCs per flight. The only significant decreases in distance flown are caused by LIGHT and NEAR at the highest density level ($p \leq 5.17E-07$, $p \leq 8.97E-05$).

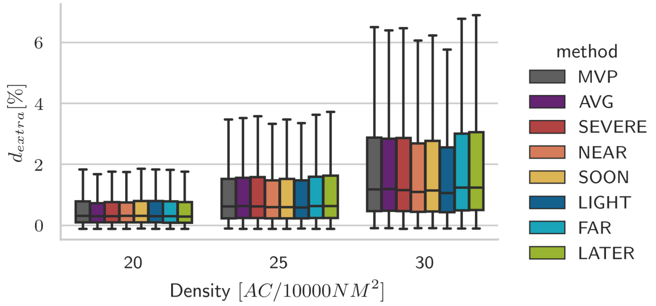


Figure 19. Extra distance flown per aircraft compared to the direct route

3) Stability: The DEP per experiment is summarized in Fig. 20. Increased air traffic densities results in increased DEP values. Although no clear effect of the weighting methods on stability is shown, also the Wilcoxon signed-rank test did not indicate any significant differences.

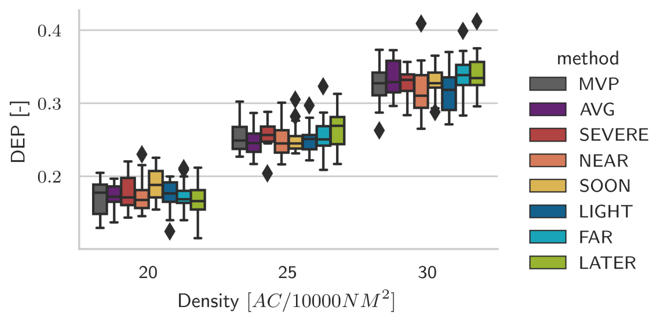


Figure 20. Domino effect parameter per experiment

VII. Discussion

In this section, first the results of synthetic multi-aircraft conflicts experiments are discussed, followed by a discussion of the results of airspace experiments.

A. Discussion of Synthetic Multi-Aircraft Conflicts

Microscopic effects of the weighted algorithms are illustrated by the results of the synthetic experiments. This section will first elaborate on the general effects of conflict design parameters on conflict resolution, then the effects of weights will be detailed.

1) General trends: The general trends are in line with the hypothesis. The cost of solving a conflict is larger at high Δt_{LoS}. In those situations one of the conflicts will have both a small time to LoS and a high intrusion, which drives larger maneuvers to solve the conflict.

The oversolved cases need a lower number of iterations compared to the undersolved cases as it is possible to directly convert to the desired conflict-free trajectory, whereas the ownship in the undersolved cases experiences resistance from the intruders. Moreover, the ownship and intruders might get in repetitive conflicts due to sequential resolution. This resistance also increases the conflict duration and number of iterations of the undersolved cases with respect to the oversolved cases.

Conflicts with relatively small conflict angles have a longer conflict duration and larger deviation. At small angles, the relative velocity is small. A velocity change towards the velocity obstacle apex could decrease the relative velocity further. The time until FTR and deviation are now larger as the aircraft fly almost parallel. At larger conflict angles, a parallel flight path is unlikely to happen as a result of conflict resolution.

An exception is found for the deviation of undersolved shallow angle conflicts and is driven by the cases where both conflicts have small angles. Then the pair-wise resolution vectors both suggest a velocity change along the velocity of the ownship and perpendicular to both conflicts. Therefore, the solution for all conflicts is close to the optimum solution. When both conflicts suggest an acceleration, both conflicts will be cooperatively solved. If one conflict suggests an acceleration and the other suggests a deceleration, the ownship sum is zero or close to zero and the conflicts will be solved one sided.

2) Conflict resolution performance of the weighted methods in oversolved multi-aircraft conflicts: The differences per method are small in the oversolved cases as a result of iterative and cooperative conflict resolution. As the pair-wise conflict resolution vectors suggest a maneuver to the same side, the solution of the intruders is not counteracted by the ownship, therefore the intruders find similar solutions in most cases.

Only the reduced step size of LIGHT leads to in increased number of iterations required to solve the conflict. By prioritizing the least urgent conflict, the ownship will only start solving the more urgent conflict once the least urgent conflict is solved. This causes an delay in the resolution of the most urgent conflict. This does, however, result in decreased conflict duration due to the decreased magnitude of the resolution vector. The reduced magnitude of the resolution vectors for AVG and SEVERE were not large enough to provide significant improvements.

At shallow angle conflicts, SEVERE and AVG showed decreased average deviation. A focus on those conflicts in the stepwise resolution, resulted in a solution closer to the optimal solution for those conflicts.

3) Conflict resolution performance of the weighted methods in undersolved multi-aircraft conflicts: The differences in undersolved situations are larger compared to oversolved cases. Especially for the number of iterations and the deviation at smaller conflict angles, improvements by prioritizing the shallow angle by NEAR are seen as a direct result of the prioritization of these conflict. FAR prioritizes the other conflict and shows increased deviation and number of iterations as a direct result of prioritizing the other conflict. At higher conflict angles reversed results are shown. More iterations also imply larger resolution vectors and therefore a smaller conflict duration. The methods requiring more iterations show therefore shorter conflict durations.

The average performance of the MACCs is shown as a function of Δt_{LoS}. Methods prioritizing more urgent conflicts result in a lower number of iterations compared to MVP, while methods prioritizing less urgent conflicts require a higher number of iterations, in line with expectations. Especially NEAR is performing well, driven by the strong performance in shallow angle conflicts. The deviation is decreased when the summed resolution vector of the ownship is closer to zero. At negative Δt_{LoS}, the pair-wise resolution vectors are similarly sized, as the closest aircraft has the smallest intrusion. AVG therefore shows the best results in this region, while also SOON and NEAR show some improvements at moderate negative Δt_{LoS}, where slight differences in resolution vectors are counteracted by weighting assigning a higher weight to the smallest resolution vector. At positive Δt_{LoS} the closest aircraft also has the largest intrusion and therefore has a larger resolution vector than the other conflict. In those MACCs it yields to prioritize the less urgent conflicts to reduce resolution of the ownship, as shown by good performance of LIGHT, FAR and LATER. The effects on conflict duration are small and mainly driven by the time to LoS, although AVG has higher conflict durations, driven by the smaller resolution vectors. LIGHT on the other hand shows good performance, while it also has a small initial resolution vector, driven by a higher number of iterations the final resolution vectors will be larger as well.

B. Discussion Airspace Experiments

In this section the conflict resolution performance in terms of safety, stability, and efficiency of the developed weighting methods is discussed. Additionally, the contradictory effects of conflict resolution in synthetic multi-aircraft conflicts and in airspace simulations is discussed.

1) Safety: The most important metrics are safety related. Where the weights which prioritize less urgent conflicts, LIGHT, FAR, and LATER, are indeed less safe. Although the cost of these methods in terms of decreased safety is higher than expected. The presence of more complex MACCs prevented the pair-wise conflict resolution by these methods as constantly less urgent conflicts were prioritized. These methods can therefore not be seen as any improvement of the unweighted MVP algorithm, although lessons can be learned from some of the specific characteristics. The weights SOON and NEAR prioritize the more urgent conflicts and have shown to do this effectively by reducing the average LoS severity significantly, as expected. SEVERE, however, did not cause an increase in safety as was expected. Fully prioritizing the most urgent conflict can be insufficient in cases where two intruders are both near a LoS.

2) Efficiency and stability: The effects of weight on the distance flown and airspace stability are small, the only significant improvements are shown by NEAR and LIGHT at the highest densities. The small effects of the weights in general can be explained by the limited differences in deviation required per method in a MACC as shown in the synthetic MACC experiments. Additionally, of most MACC situations, at least one conflict had a intrusion below 1 NM, as shown in Appendix E. The effect of the weighted methods is small for those conflicts due to the low number of iterations required to solve them, as shown in Appendix C. The DEP lacks significant differences in the results, although the methods do show high and low DEP values compared to the MVP algorithm per simulation. As only 15 repetitions were performed per density level, the results rely on a few samples and might get more significant for an increased number of repetitions.

The effects of weights in general increase at higher traffic densities, at higher densities more conflicts occur due to the larger area of space occupied by aircraft and their protected zone. A higher number of conflicts increases the probability that two conflicts occur at the same time. Additionally, at higher traffic densities, it is more likely to conflict with a nearby aircraft as a result of conflict resolution. In this way, conflict chains exist, which are solved slower due to the restricted movement of the aircraft involved. A higher number of iterations and weighted iterations are needed to solve those conflicts and therefore the effects of weights increase. This also explains why the number of iterations required to solve a conflict is higher in the airspace simulations compared to the synthetic situations.

The lower iterations required by NEAR translates result in a lower number of complex conflict chains and therefore a lower distance flown. As the deviations can get particularly large for more complex MACCs, where not only the ownship is in conflict with multiple intruders but the intruders are also in conflict with other aircraft, as shown in Appendix E. When all those conflicts are undersolved, the divergence of the ownship in the first MACC does not only affect those intruders but also the intruders which are in the next MACC. The conflicts are all connected due to the iterative solving. In this chain reaction, the resolution of one conflict can affect the resolution of conflicts far away. Therefore, a large deviation is experienced less frequently, decreasing the distance flown. Additionally, a fast convergence to a solution is more important than a solution with a lower deviation as was expected. That is why NEAR shows the best performance in terms of flight efficiency.

VIII. Recommendations

In the airspace simulations, reducing the number of iterations required to solve a multi-aircraft conflict is shown most effective to also reduce the number of multi-aircraft conflicts and the average distance flown. NEAR determines the weight of a conflict based on the ratio between the average distance between the ownship and all intruders and the distance between the intruder of that conflict and the ownship. This method successfully reduces the number of iterations, especially at small conflict angles. Although little effort has been put into fine-tuning the weights for the optimal solution. It would be interesting to investigate whether a more sophisticated weighting method would be more successful in doing this. Explicit use of conflict angles or velocity obstacle locations could potentially be valuable.

The MACC analysis in this study is limited to an ownship in conflict with two intruders and the intruders are able to move freely. At high densities, situations where intruders are in conflict with other aircraft as well occur more often and lead to poorly solved conflict chains. More detailed analysis of conflict chains can lead to insights on how to decrease the negative effects. It would be interesting to investigate the addition of vertical maneuvers, as a way to break up complex conflict chains faster. Another interesting option would be to investigate the possibility of varying the iteration speed per aircraft. This would reduce the high dependency on the maneuver of the intruder and might break conflict chains. Moreover, unequal iteration speeds could be a way to model pilot behavior.

The airspace simulations have shown limitations in terms of significance. The stability and efficiency measures are at the edge of significance. Increased flight time, experiment time, or number of repetitions could show if this is due to limited experiments or due to the limited effects of the weights. In a later stadium it would also be interesting to investigate the effects of wind and turbulence, as this will limit the maneuver possibilities and therefore the resolution trajectories.

IX. Conclusion

This research presents an investigation into extending the Modified Voltage Potential algorithm as conflict detection and resolution method in a horizontal free flight environment, by weighting the pair-wise resolution vectors of the Modified Voltage Potential in multi-aircraft conflicts.

The first part of this research has analysed multi-aircraft conflicts in general and distinguished two types of multi-aircraft conflicts. One where all conflicts suggest a maneuver to the same side, in this case the summed resolution vector is larger than necessary and solution will therefore overshoot the minimum required solution. This situation is called oversolved. The other type is where the pair-wise resolution vectors suggest counteracting maneuvers, in this situation the summed resolution vector does not suggest a conflict-free trajectory instantaneous. This situation is called undersolved. The conflict detection and resolution systems in this research relied on continuous situation analysis. Every second, the situation is revised and a new resolution is calculated by the Modified Voltage Potential algorithm and executed directly by the aircraft. This iterative solving reduces the overshoot in oversolved cases and ensures that undersolved cases find a conflict-free trajectory.

This iterative solving also limits the effect of weights. It is shown that the effects of weights in oversolved cases are small in terms of path deviation, conflict duration, and the number of iterations to solve the conflicts. Effects in undersolved situations were larger. By prioritizing more urgent conflicts, solutions were found faster, although at a cost of higher path deviations. On the other hand, prioritizing less urgent conflicts decreased deviations at a cost of a larger number of iterations.

Various weighted methods have been tested in experiments simulating the airspace. At densities of 20 and 25 $AC/10,000$ NM^2 the effects of weights are insignificant, due to the low number of multi-aircraft conflicts and the limited effect of weights on these situations. At a density of 30 $AC/10,000$ NM^2 the number of multi-aircraft conflicts increased and the importance of finding a solution with the least number of iterations got more pressing, to avoid complex multi-aircraft conflicts with many aircraft involved, as those situations require higher deviations to solve. The weight prioritizing aircraft which were at a shorter distance proved to be efficient in finding faster solutions in complex situations. Which reduces the extra distance flown due to conflict resolution. Moreover, this method ensured an increase in safety.

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II

Scientific Paper Appendices

A
Airspace Analysis

The figures presented in this chapter serve as validation of the experiment composition and show the characteristics of a scenario where aircraft do not use a CR algorithm. The density is set at 24.5 AC/10000 NM^2, the experiment starts after 3600 seconds and ends after 12600 seconds. The experiment borders are at +/- 1.78 degrees latitude and longitude.

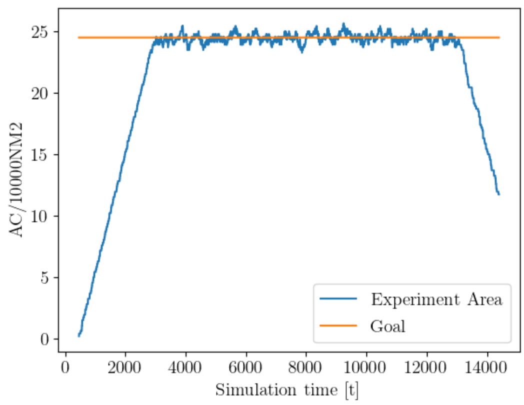


Figure A.1: The density is quite constant and at the expected level for the duration of the experiment. An steady density increase is seen during the 3000 second build-up period. After the experiment ends the density decreases as no more aircraft are spawned.

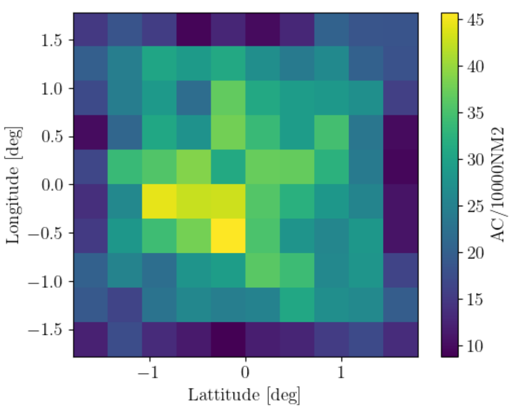


Figure A.2: The density distribution in the experiment area during the experiment. The density is lower at the borders and increases near the center due to the route generation logic.

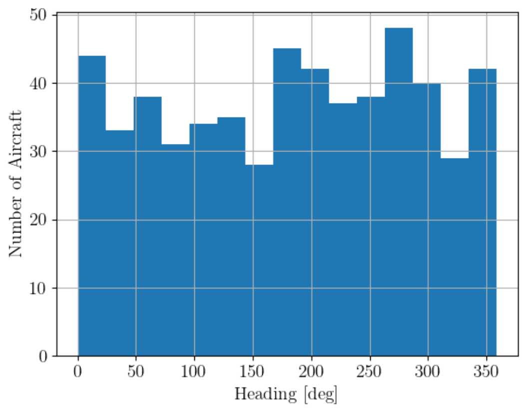


Figure A.3: The heading distribution in the experiment area during the experiment. The distribution is not completely uniform as the number of aircraft per bin is relatively low and heading is generated using a random sampling algorithm for a uniform distribution

B

Results of Wilcoxon Signed Rank Test of Synthetic Experiments

In this appendix the results of all Wilcoxon signed rank tests the synthetic experiments as discussed in the paper are presented. Differences between the results per method are deemed significant when $p \leq 0.05$ Since the unweighted method is compared to seven weighted methods per density, a Bonferroni correction was adjusted. Therefore, the null hypothesis will be rejected and the difference between the results will be regarded significant when $p \leq 0.0071$. Values deemed as significant improvements of the means with respect to MVP are presented in **bold**. Blank items indicate that the results were exactly the same.

Table B.1: P values of Wilcoxon Signed Rank Tests on the deviation of oversolved situations per conflict angle

Conflict Angle [deg]	**165**	**135**	**105**	**75**	**45**	**15**
AVG	0.273	0.263	0.731	0.700	0.977	**0.000**
SEVERE	0.170	0.271	0.714	0.496	0.009	**0.000**
NEAR	0.264	0.092	0.080	0.477	0.247	0.016
SOON	0.293	0.177	0.287	0.689	0.335	0.604
LIGHT	0.234	0.154	0.915	0.906	0.983	0.098
FAR	0.528	0.736	0.791	0.230	0.018	0.135
LATER	0.887	0.688	0.940	0.107	0.240	0.453

Table B.2: P values of Wilcoxon Signed Rank Tests on the number of iterations of oversolved situations per conflict angle

Conflict Angle [deg]	**165**	**135**	**105**	**75**	**45**	**15**
AVG			0.157	0.026	**0.001**	0.484
SEVERE	0.063	0.746	0.026	**0.002**	**0.000**	0.402
NEAR		0.063		0.201	0.975	**0.002**
SOON				**0.004**	0.844	0.094
LIGHT	**0.000**	**0.000**	0.026	0.052	**0.000**	0.105
FAR		0.157	0.157	0.026	0.237	**0.000**
LATER		0.157		0.157	0.504	0.068

Table B.3: P values of Wilcoxon Signed Rank Tests on the conflict duration of oversolved situations per conflict angle

Conflict Angle [deg]	**165**	**135**	**105**	**75**	**45**	**15**
AVG	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.777
SEVERE	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.144
NEAR	**0.000**	**0.000**	**0.000**	0.572	0.265	0.217
SOON	**0.000**	0.016	**0.000**	0.310	0.118	0.708
LIGHT	0.011	**0.006**	**0.000**	0.274	**0.002**	0.235
FAR	**0.000**	**0.006**	0.112	0.090	0.527	0.922
LATER	**0.000**	**0.004**	**0.004**	0.037	0.722	0.072

Table B.4: P values of Wilcoxon Signed Rank Tests on the deviations of undersolved situations per conflict angle

Conflict Angle [deg]	**165**	**135**	**105**	**75**	**45**	**15**
AVG	0.062	0.068	0.127	0.174	0.876	0.101
SEVERE	**0.000**	**0.000**	0.057	0.931	0.695	0.048
NEAR	**0.007**	0.028	0.033	0.503	0.223	**0.001**
SOON	0.415	0.310	0.228	0.490	0.265	0.739
LIGHT	0.871	0.648	0.459	0.247	0.280	0.023
FAR	**0.000**	**0.000**	0.008	**0.001**	0.031	0.039
LATER	0.415	0.095	**0.002**	**0.004**	0.755	0.813

Table B.5: P values of Wilcoxon Signed Rank Tests on the number of iterations of undersolved situations per conflict angle

Conflict Angle [deg]	**165**	**135**	**105**	**75**	**45**	**15**
AVG	0.042	0.232	0.202	0.830	0.934	0.026
SEVERE	**0.000**	**0.000**	**0.000**	0.430	0.487	0.218
NEAR	**0.000**	**0.000**	**0.000**	0.018	**0.000**	**0.000**
SOON	0.393	0.445	0.043	0.021	0.758	0.666
LIGHT	**0.001**	**0.004**	**0.002**	0.848	0.061	0.835
FAR	0.011	0.009	0.008	0.014	**0.000**	**0.000**
LATER	0.184	**0.003**	**0.000**	**0.003**	0.063	0.861

Table B.6: P values of Wilcoxon Signed Rank Tests on the conflict duration of undersolved situations per conflict angle

Conflict Angle [deg]	**165**	**135**	**105**	**75**	**45**	**15**
AVG	**0.000**	**0.001**	**0.002**	0.170	**0.000**	0.737
SEVERE	0.235	**0.002**	**0.005**	0.070	**0.004**	0.827
NEAR	0.710	0.009	**0.004**	0.040	0.260	0.757
SOON	0.075	**0.003**	**0.004**	0.019	0.820	0.721
LIGHT	**0.000**	**0.000**	**0.001**	0.226	**0.000**	0.091
FAR	0.785	**0.000**	0.017	0.057	0.864	0.051
LATER	0.528	0.008	0.887	0.485	**0.000**	0.208

Table B.7: P values of Wilcoxon Signed Rank Tests on the deviations of oversolved situations per Δt_{LoS} $[s]$

Δt_{LoS} $[s]$	**-200**	**-150**	**-100**	**-50**	**0**	**50**	**100**	**150**	**200**
AVG	**0.007**	0.041	0.116	0.023	0.244	0.027	0.288	0.503	0.886
SEVERE	0.055	**0.005**	0.242	0.089	0.853	0.144	0.068	0.583	0.392
NEAR	0.243	0.148	0.058	0.404	0.740	0.814	0.751	0.945	0.350
SOON	0.016	0.742	0.453	0.814	0.625	0.396	0.060	0.145	0.569
LIGHT	0.291	0.659	0.476	0.442	0.708	0.856	0.152	0.165	0.946
FAR	0.330	0.041	0.240	0.114	0.486	0.444	0.397	0.682	0.428
LATER	0.575	0.169	0.060	0.411	0.780	0.315	0.775	0.240	0.232

Table B.8: P values of Wilcoxon Signed Rank Tests on the number of iterations of oversolved situations per Δt_{LoS} [s]

Δt_{LoS} [s]	**-200**	**-150**	**-100**	**-50**	**0**	**50**	**100**	**150**	**200**
AVG	0.321	0.321	0.283	0.281	**0.001**	**0.000**	0.007	0.029	0.275
SEVERE	**0.002**	0.440	0.758	0.403	0.021	0.013	0.094	0.079	0.033
NEAR	0.345	0.197	0.108	0.045	0.614	0.593	0.073	0.015	0.414
SOON	1.000	0.384	**0.001**	1.000	0.235	0.157	0.063	0.107	0.107
LIGHT	**0.006**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.001**	**0.000**	**0.000**
FAR	0.079	0.269	0.637	0.593	0.157	1.000	**0.005**	1.000	0.046
LATER	0.222	0.235	0.157	0.414	0.157	0.457	1.000	0.479	0.749

Table B.9: P values of Wilcoxon Signed Rank Tests on the conflict duration of oversolved situations per Δt_{LoS} [s]

Δt_{LoS} [s]	**-200**	**-150**	**-100**	**-50**	**0**	**50**	**100**	**150**	**200**
AVG	**0.000**	**0.000**	0.010	0.165	0.382	0.039	0.016	0.017	0.561
SEVERE	**0.000**	**0.002**	**0.005**	0.026	0.256	0.795	0.651	0.308	0.700
NEAR	0.681	0.413	0.238	0.734	0.073	0.459	0.501	0.796	0.264
SOON	0.665	0.484	0.628	0.477	0.131	0.914	0.296	0.277	0.523
LIGHT	**0.000**	0.592	**0.001**	0.013	0.030	**0.001**	**0.000**	**0.000**	**0.000**
FAR	0.048	0.349	0.728	0.459	0.158	0.623	0.626	0.141	0.334
LATER	0.209	0.584	0.969	0.509	0.902	0.734	0.582	0.867	0.978

Table B.10: P values of Wilcoxon Signed Rank Tests on the deviations of undersolved situations per Δt_{LoS} [s]

Δt_{LoS} [s]	**-200**	**-150**	**-100**	**-50**	**0**	**50**	**100**	**150**	**200**
AVG	0.813	**0.000**	**0.000**	**0.000**	**0.000**	0.599	0.016	0.674	0.670
SEVERE	0.678	0.388	0.017	**0.001**	0.045	**0.000**	0.024	**0.003**	0.902
NEAR	0.580	0.032	**0.000**	**0.000**	0.319	**0.000**	0.020	**0.000**	0.624
SOON	0.030	0.329	**0.001**	**0.000**	0.516	**0.000**	0.059	**0.001**	0.825
LIGHT	0.203	0.509	0.383	0.059	0.136	0.614	**0.001**	**0.000**	**0.000**
FAR	0.705	0.187	**0.002**	0.569	0.847	0.803	**0.000**	**0.000**	**0.000**
LATER	0.602	**0.001**	**0.000**	**0.004**	0.131	0.573	**0.000**	**0.000**	**0.000**

Table B.11: P values of Wilcoxon Signed Rank Tests on the number of iterations of undersolved situation per Δt_{LoS} [s]

Δt_{LoS} [s]	**-200**	**-150**	**-100**	**-50**	**0**	**50**	**100**	**150**	**200**
AVG	0.798	**0.000**	**0.000**	0.405	0.012	0.975	**0.005**	**0.000**	**0.000**
SEVERE	0.008	**0.000**	0.164	0.616	0.021	**0.000**	**0.000**	**0.000**	**0.000**
NEAR	**0.000**	0.798	0.057	**0.003**	**0.000**	0.110	0.146	0.810	0.018
SOON	**0.002**	0.034	0.151	0.603	0.235	**0.003**	0.140	0.023	0.013
LIGHT	0.485	0.033	0.458	0.746	0.410	**0.002**	0.043	0.057	**0.001**
FAR	**0.006**	**0.000**	**0.000**	**0.001**	0.199	**0.000**	**0.001**	0.023	0.011
LATER	**0.000**	**0.000**	0.009	0.316	0.414	**0.002**	0.268	0.152	**0.002**

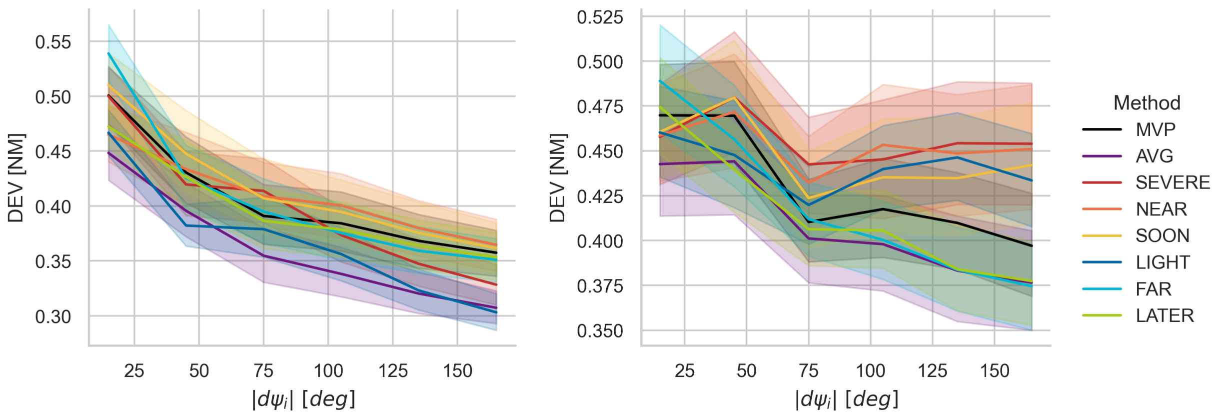
Table B.12: P values of Wilcoxon Signed Rank Tests on the conflict duration of undersolved situation per Δt_{LoS} [s]

Δt_{LoS} [s]	**-200**	**-150**	**-100**	**-50**	**0**	**50**	**100**	**150**	**200**
AVG	**0.001**	**0.000**	**0.000**	0.024	0.717	**0.000**	**0.000**	**0.000**	**0.000**
SEVERE	0.034	0.014	0.027	0.018	0.594	0.148	0.055	0.043	**0.003**
NEAR	0.500	**0.000**	**0.000**	0.411	0.615	0.544	0.027	0.574	**0.000**
SOON	0.576	**0.000**	**0.002**	0.507	0.309	0.455	0.037	0.044	**0.000**
LIGHT	0.127	**0.000**	**0.000**	0.010	**0.005**	0.129	0.575	**0.000**	**0.000**
FAR	**0.001**	**0.005**	0.008	**0.005**	**0.000**	0.455	0.384	0.498	**0.002**
LATER	**0.001**	0.255	0.679	0.872	**0.001**	0.205	0.326	0.820	**0.000**

C

Detailed results of grid simulations

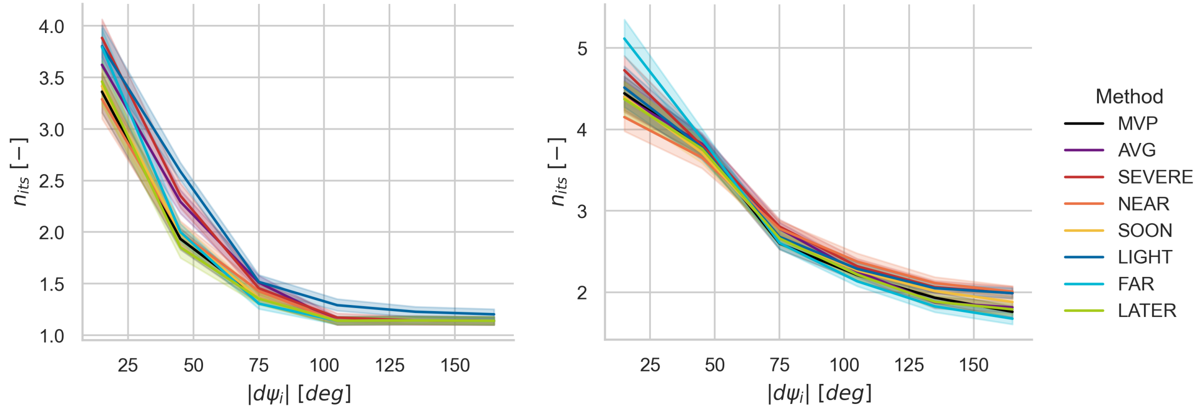
In addition to the synthetic MACC experiments as presented in the paper, a set of experiments is performed with different initial predicted distances to CPA. In this appendix, the results of two sets of experiments are presented. In both sets the distance to CPA of intruder one is 4.5 NM. In set one, the distance to CPA of intruder two is 4.5 NM as well. This set only contains positive Δt_{LOS} as negative Δt_{LOS} situations would have the same symmetry. In set two, the distance to CPA of intruder two is 0.5 NM. The results show similar behavior compared to the experiments presented in the paper, confirming that the mechanics shown indeed are applicable to a wider range of multi-aircraft conflicts.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

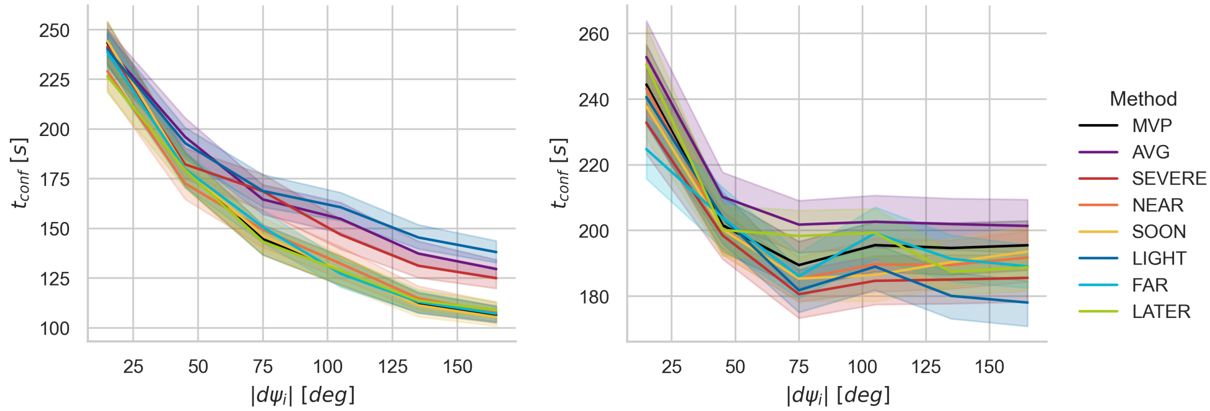
Figure C.1: The effects of weighted methods on the average deviation as function of the conflict angle. The lines represents the mean and the shading represents the 95% confidence intervals The initial predicted distance to CPA of intruder two is 4.5 NM..



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

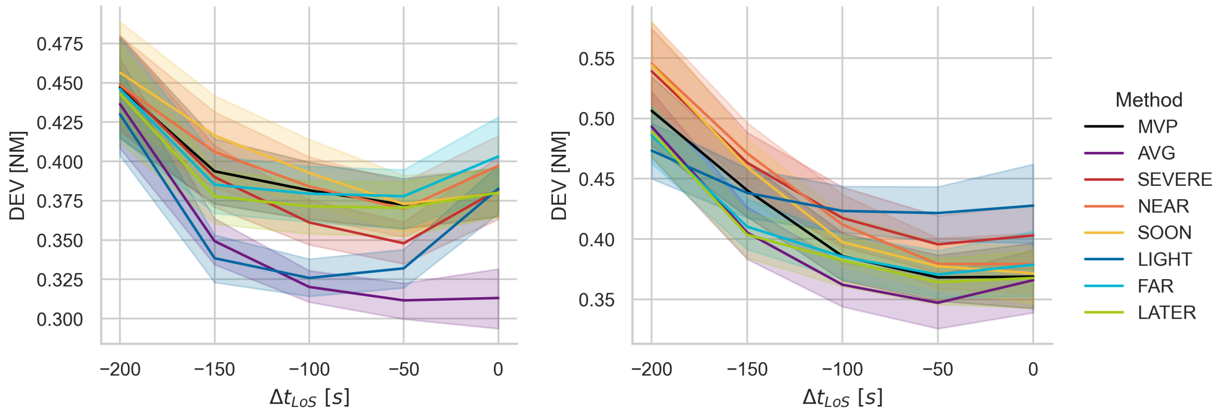
Figure C.2: The effects of weighted methods on the average number of iterations as function of the conflict angle. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 4.5 NM.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

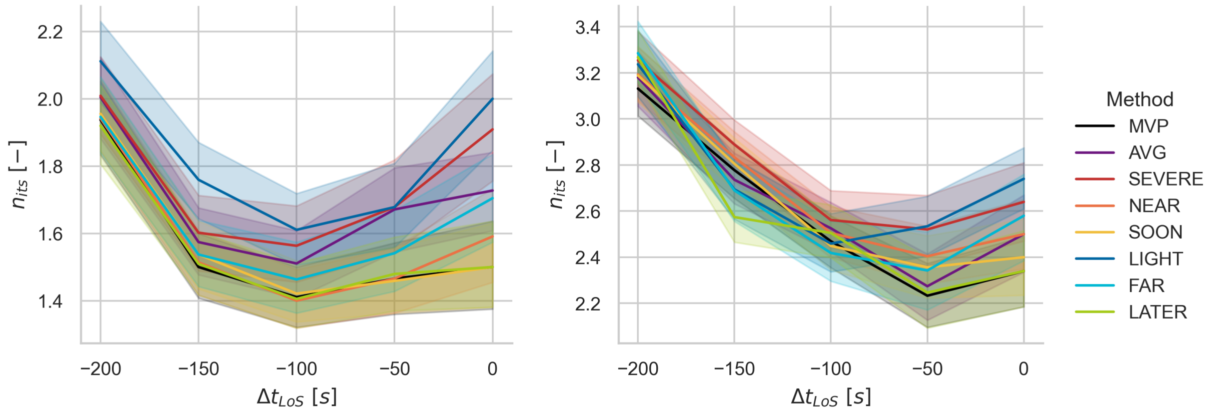
Figure C.3: The effects of weighted methods on the average conflict duration as function of the conflict angle. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 4.5 NM.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

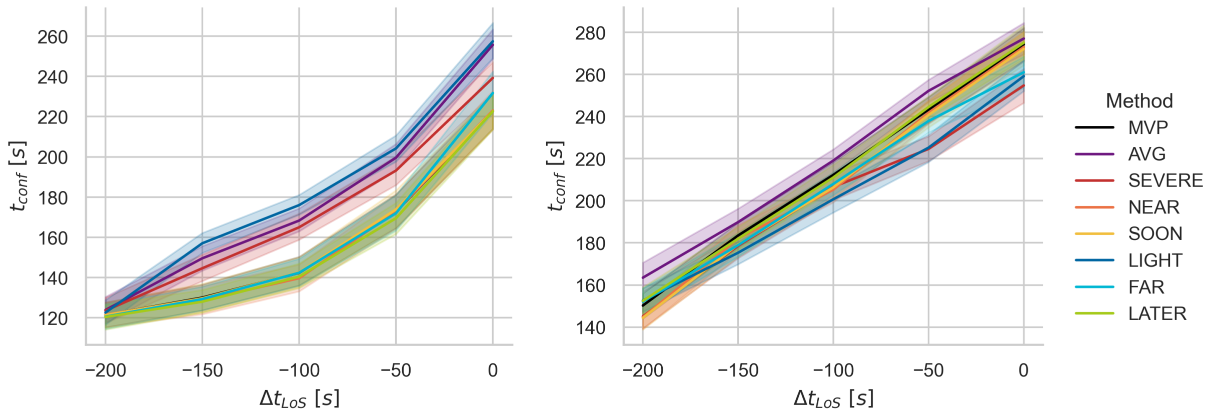
Figure C.4: The effects of weighted methods on the average deviation as function of Δt_{LOS}. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 4.5 NM.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

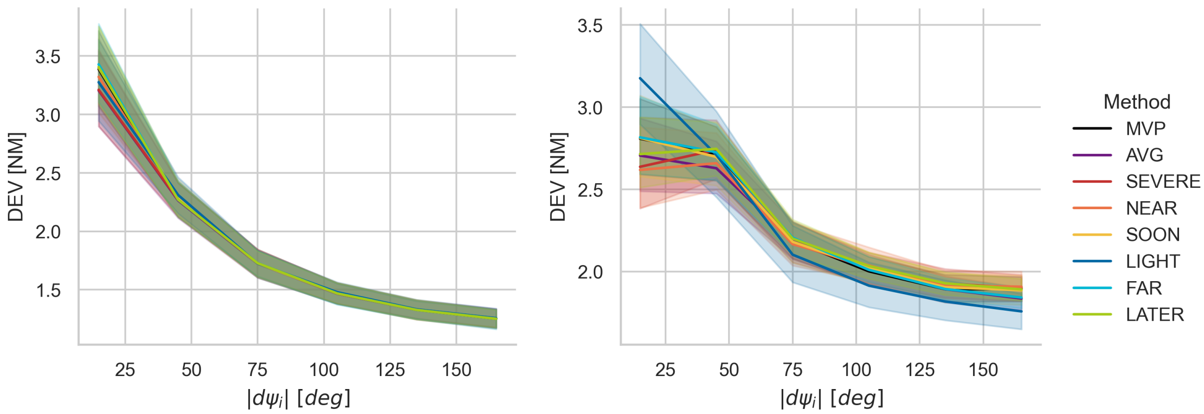
Figure C.5: The effects of weighted methods on the average number of iterations as function of Δt_{LOS}. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 4.5 NM.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

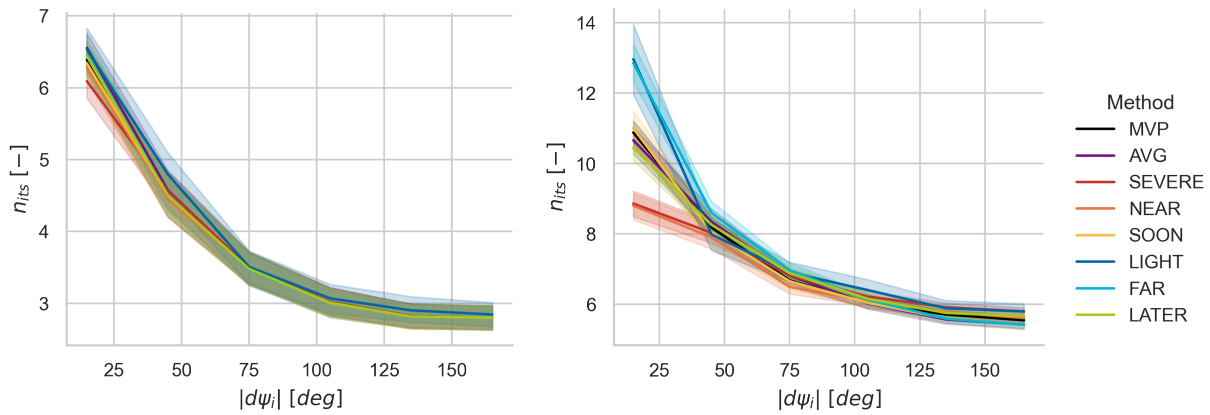
Figure C.6: The effects of weighted methods on the average conflict duration as function of Δt_{LOS}. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 4.5 NM.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

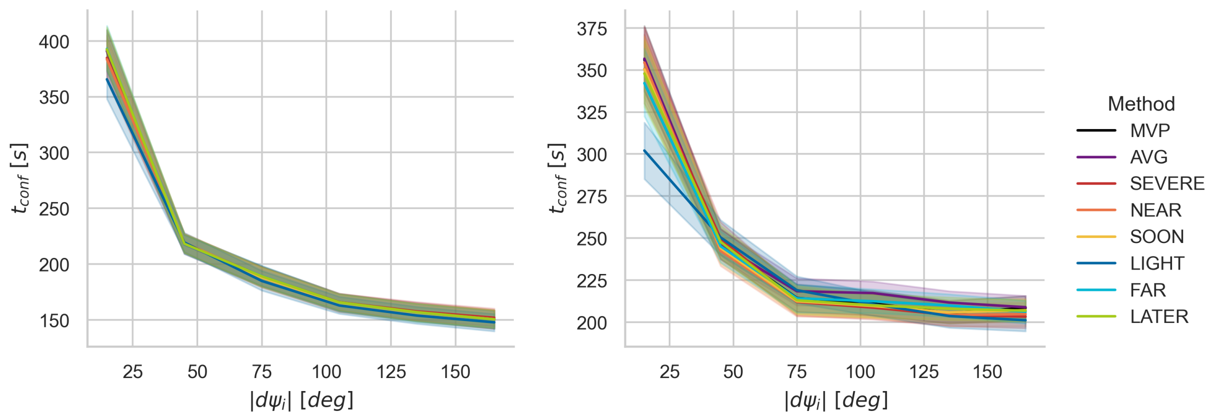
Figure C.7: The effects of weighted methods on the average deviation as function of the conflict angle. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 0.5 NM.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

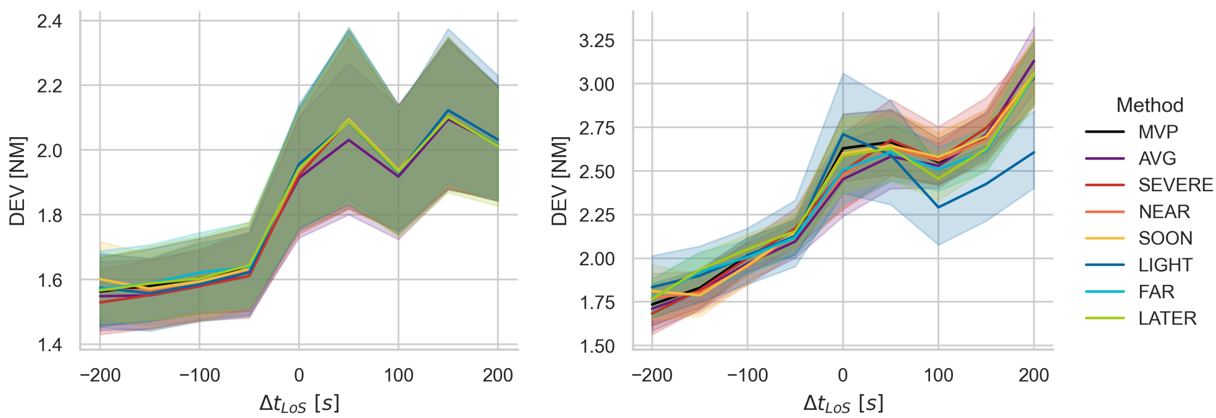
Figure C.8: The effects of weighted methods on the average number of iterations as function of the conflict angle. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 0.5 NM.



(a) Results of oversolved MACC situations

(b) Results of undersolved MACC situations

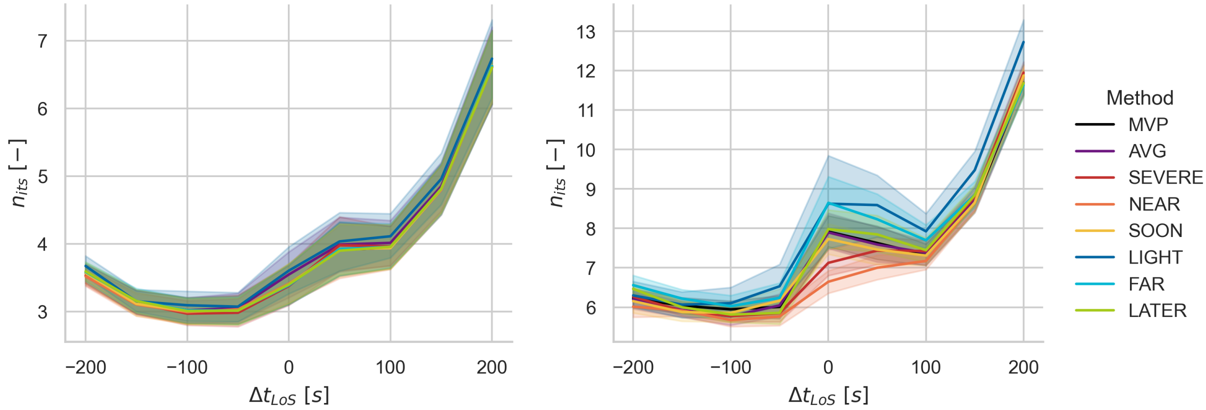
Figure C.9: The effects of weighted methods on the average conflict duration as function of the conflict angle. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 0.5 NM.



(a) Results of oversolved MACC situations

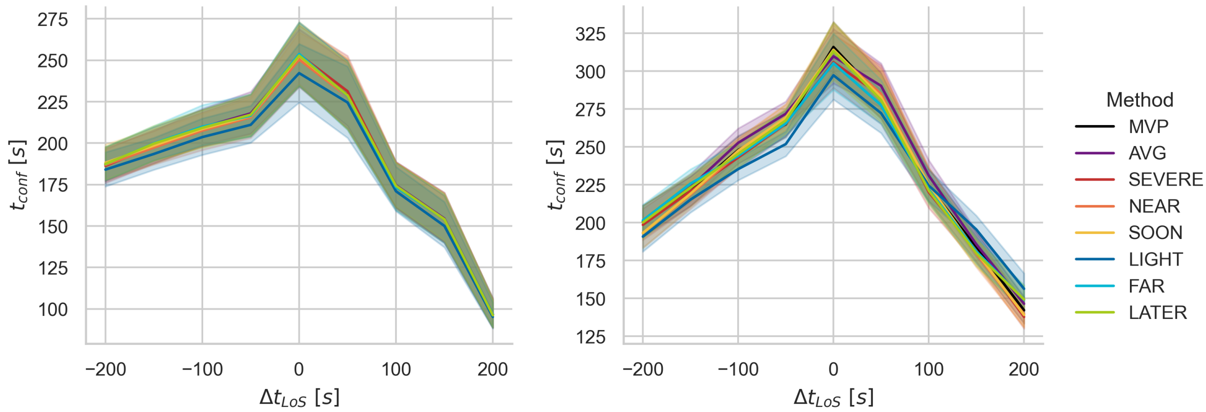
(b) Results of undersolved MACC situations

Figure C.10: The effects of weighted methods on the average conflict duration as function of Δt_{LOS}. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 0.5 NM.



(a) Results of oversolved MACC situations (b) Results of undersolved MACC situations

Figure C.11: The effects of weighted methods on the average conflict duration as function of Δt_{LOS}. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 0.5 NM.



(a) Results of oversolved MACC situations (b) Results of undersolved MACC situations

Figure C.12: The effects of weighted methods on the average conflict duration as function of Δt_{LOS}. The lines represents the mean and the shading represents the 95% confidence intervals. The initial predicted distance to CPA of intruder two is 0.5 NM.

D

Results of Wilcoxon Signed Rank Test and Mann-Whitney U Tests of Airspace Experiments

In this appendix the results of all Wilcoxon signed rank tests and Mann-Whitney U tests of the airspace experiments are presented. Differences between the results per method are deemed significant when $p \leq 0.05$ Since the unweighted method is compared to seven weighted methods per density, a Bonferroni correction was adjusted. Therefore, the null hypothesis will be rejected and the difference between the results will be regarded significant when $p \leq 0.0071$. Values deemed as significant improvements of the means with respect to MVP are presented in **bold**. Significant results which are worse than MVP are presented in *italic.*

Table D.1: P values of Wilcoxon Signed Rank Tests on the distance flown per flight

Instantaneous AC [−]	**187**	**234**	**281**
AVG	4.75E-02	5.53E-01	9.72E-01
SEVERE	8.75E-02	6.69E-01	3.74E-01
NEAR	3.35E-01	1.43E-01	**8.97E-05**
SOON	4.79E-01	3.55E-01	9.99E-02
LIGHT	7.83E-01	6.00E-02	**5.17E-07**
FAR	7.62E-01	1.51E-01	9.25E-02
LATER	8.34E-02	2.47E-02	4.32E-02

Table D.2: P values of Wilcoxon Signed Rank Tests on the DEP per experiment

Instantaneous AC [−]	**187**	**234**	**281**
AVG	6.50E-01	3.63E-01	3.07E-01
SEVERE	1.73E-01	5.70E-01	8.65E-01
NEAR	6.09E-01	6.09E-01	2.33E-01
SOON	8.98E-03	9.10E-01	3.63E-01
LIGHT	8.26E-01	9.55E-01	1.25E-01
FAR	2.72E-01	2.81E-01	1.25E-01
LATER	6.09E-01	1.56E-01	9.95E-02

Table D.3: P values of Wilcoxon Signed Rank Tests on the number of LoS per experiment

Instantaneous AC [−]	**187**	**234**	**281**
AVG	5.18E-01	7.02E-01	4.66E-01
SEVERE	1.00E+00	6.95E-01	3.23E-01
NEAR	9.16E-01	5.48E-01	1.15E-01
SOON	1.09E-01	1.52E-01	4.39E-01
LIGHT	*7.82E-04*	*2.55E-03*	*6.50E-04*
FAR	2.76E-02	3.21E-02	*6.32E-04*
LATER	7.00E-02	*1.44E-03*	*6.50E-04*

Table D.4: P values of Wilcoxon Signed Rank Tests on the number of MACC per experiment

Instantaneous AC [−]	**187**	**234**	**281**
AVG	3.00E-01	3.91E-01	9.38E-02
SEVERE	*3.91E-04*	*4.49E-11*	*4.94E-11*
NEAR	4.18E-01	2.03E-01	**4.29E-06**
SOON	4.44E-01	9.73E-02	**4.78E-04**
LIGHT	5.95E-01	9.27E-01	**9.91E-04**
FAR	1.51E-01	2.17E-02	*1.26E-06*
LATER	9.37E-01	*2.22E-06*	*4.06E-10*

Table D.5: P values of Mann-Whitney U Tests on the number of iterations per MACC

Instantaneous AC [−]	**187**	**234**	**281**
AVG	3.60E-01	4.49E-02	1.19E-01
SEVERE	4.78E-01	2.29E-01	4.05E-02
NEAR	1.96E-01	4.19E-01	**6.55E-03**
SOON	3.49E-01	1.31E-02	**3.86E-03**
LIGHT	3.60E-01	2.54E-02	**4.99E-06**
FAR	2.83E-01	3.24E-01	5.60E-02
LATER	3.38E-01	1.13E-02	2.21E-02

Table D.6: P values of Mann-Whitney U Tests on the LoS Severity per LoS

Instantaneous AC [−]	**187**	**234**	**281**
AVG	9.29E-02	3.23E-01	9.04E-02
SEVERE	4.23E-02	9.41E-02	3.95E-01
NEAR	2.03E-01	8.99E-03	**2.39E-04**
SOON	1.38E-01	1.75E-01	**9.71E-04**
LIGHT	*3.27E-04*	*1.32E-07*	*9.54E-12*
FAR	*3.46E-03*	*1.67E-04*	*7.62E-04*
LATER	*8.54E-04*	*2.38E-09*	*2.92E-15*

E

Detailed results of MACC in airspace simulations

In this chapter, more detailed information about the MACC geometries and resolution performance in the airspace simulations is presented. The geometries are limited to two intruders per MACC, this accounts for around 85% of the MACC situations.

In Figure E.1 it is shown that the majority of the conflicts has a Δd_{CPA} below one and that most MACCs have small Δt_{LoS}. Those conflicts both have a high Δd_{CPA} and relatively high Δt_{LoS}, driven by conflict resolution progress made by pair-wise conflicts before it becomes a MACC. Additionally, it is likely that the ownship conflicts with a second intruder due to a conflict resolution maneuver. In this case, the time to LoS might be smaller than the look-ahead time but the intrusion will be low.

In Figure E.2 it is shown that a slight majority of the MACC contains at least one shallow angle conflict, caused by an increased number of iterations required to solve shallow angle conflicts.

In fig. E.3 it is shown that the average deviation of an aircraft part of a conflict chain is higher than in a MACC, which is higher than a pair-wise conflict. At the highest density, LIIGHT shows the largest decrease in deviation in those conflict chains. Additionally, it shown that the number of iteratations required to solve a conflict part of a conflict chain is higher than in a MACC, which is higher than a pair-wise conflict. At the highest density, NEAR shows the largest decrease in deviation in those conflict chains.

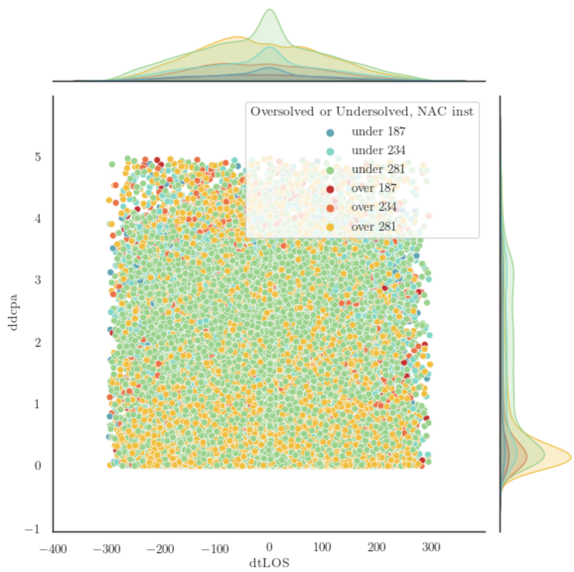


Figure E.1: Distribution of $\Delta d_{CPA} = ddcpa$ and $\Delta t_{LoS} = dtLOS$ parameters at the start of MACCs containing two intruders in airspace experiments with MVP as conflict resolution method.

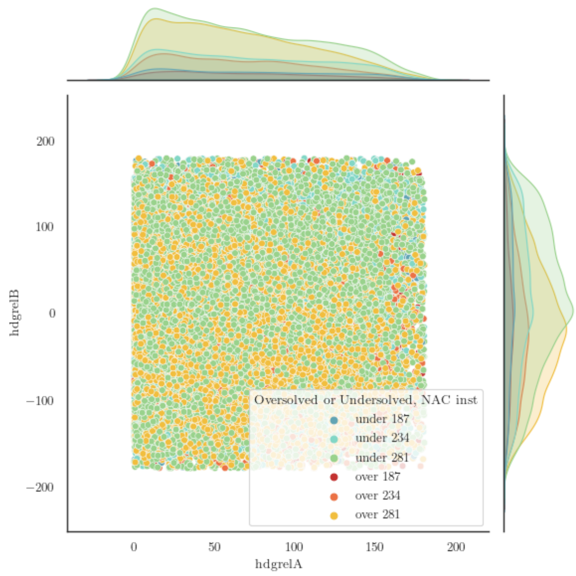


Figure E.2: Distribution of $d\psi_1 = hdgrelA$ and $d\psi_2 = hdgrelB$ parameters at the start of MACCs containing two intruders in airspace experiments with MVP as conflict resolution method.

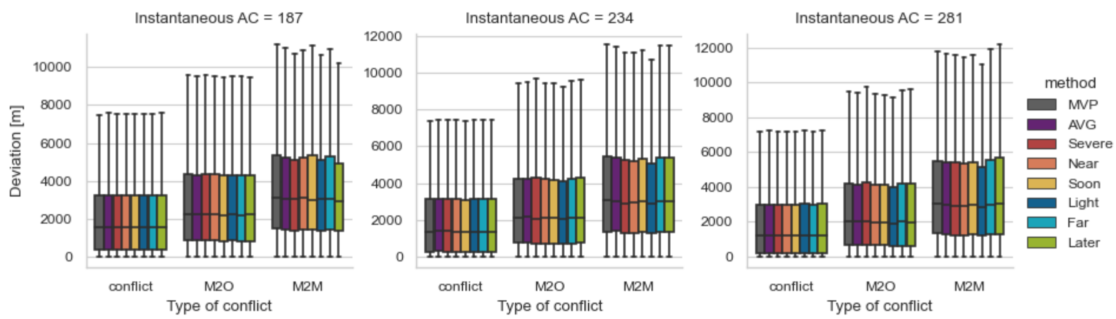


Figure E.3: The deviation per aircraft per conflict type grouped by experiment. M2O stands for multiple intruders to a single ownship. M2M stands for multiple intruders to multiple intruders, so a MACC chain. The number of instantaneous aircraft are as in the low, medium and high densities of the airspace experiments.

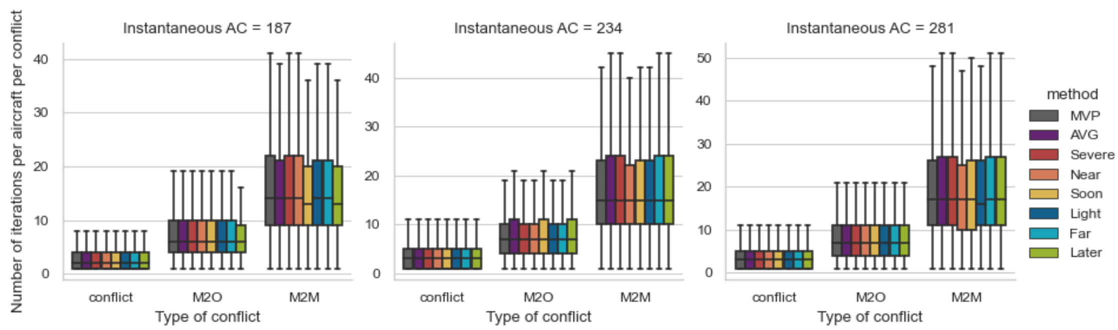


Figure E.4: The number of iterations per aircraft per conflict type grouped by experiment. M2O stands for multiple intruders to a single ownship. M2M stands for multiple intruders to multiple intruders, so a MACC chain. The number of instantaneous aircraft are as in the low, medium and high densities of the airspace experiments.

III

Preliminary Report [already graded]

1
Introduction

Over the last decades, a strong increase in air traffic has been seen, Eurocontrol [3]. Airlines willingly answered to the growing passenger demand by increasing the number of routes and increasing the frequency of flights. Now that the Covid-19 virus has taken hold of the world, the flight activity is very low. Although, there will come a time that the virus is beaten and surely air traffic will increase again. With increasing aircraft activity, the tension on the air traffic management (ATM) systems grows, causing delays and increased flight distance. Which results in increased cost and pollution. In times of economic increased environmental awareness and possibly economic downturn due to the pandemic, increasing flight efficiency is more important than ever.

With increased awareness of route inefficiencies already in the 1990s, the idea of flying direct routes between the origin and destination instead of following predefined by ATM gained the interest of the aviation industry. Although, this comes with challenges. The routes are currently predefined to create a clear and manageable overview of the airspace, so that air traffic controllers can better separate traffic to ensure safety. When aircraft would be flying randomly through the airspace, it would no longer be possible for air traffic controllers to ensure safe separation.

This lead to the development of the free flight concept, which moves the responsibility of traffic separation away from the air traffic control towards the cockpit, RTCA [16], Uni et al. [22]. The on-board organisation of safe separation from other aircraft, without interference of a centralized organization, is called self-separation. To assist the pilots in bearing this heavy responsibility, they are assisted by an on-board algorithm which detects conflicts by propagating state data and suggests a maneuver to prevent a loss of separation (LoS). This information is then shared with the pilots. Research in the area of self-separation focuses mainly on three elements, conflict detection (CD), conflict resolution (CR), and conflict prevention (CP).

The Modified Voltage Potential algorithm is a conflict detection and resolution system developed by Hoekstra et al. [8], it ensures this separation by tactical and implicitly coordinated maneuvers. Pair-wise conflict resolution vector vectors are calculated based on the principle of charged particles which repel and keep separated in that way. This relative straight forward algorithm is well thought out for conflicts involving two aircraft. When more aircraft are involved in the conflict, the pair-wise resolution vectors are simply summed, as with the repelling forces acting on charged particles. Improvements could potentially be made with respect to the resolution efficiency in some cases where more than two aircraft are in conflict at once. This study will investigate multi-aircraft conflict resolution mechanics by the modified voltage potential algorithm and the potential effects of weighting the pair-wise avoidance vectors, in an effort to advice a weighting to improve the current situation.

1.1. Thesis Objective and Research approach

This thesis will work towards the objective stated below, with the help of research approach as is described in section 1.1.1.

> Investigate the possibilities to improve multi-aircraft conflict resolution efficiency and safety, and decrease the destabilizing effects on the airspace when the Modified Voltage Potential Algorithm is used as CR method, by means of a weighted sum of the pairwise conflict resolution vectors.

1.1.1. Research Approach

The research activities are carried out as shown in the flow in fig. 1.1. The figure shows the iterative nature of this research. The benefit of iterating through the process is that it will provide extra insight. The downside is that there is no clear end to the process and therefore the time needed can exceed the time available for this thesis. Therefore, both the problem identification and the weight development process are looped through a maximum of two times.

In this report a first time is looped through the full system. In the second part of the study, the categorisation will be analysed based on insights gained from the latest experiments done as presented in chapter 7. Based on those insights potential improvements will be further analysed and translated to new weighting methods. The last experiments will test these methods and conclusions will be drawn upon the results

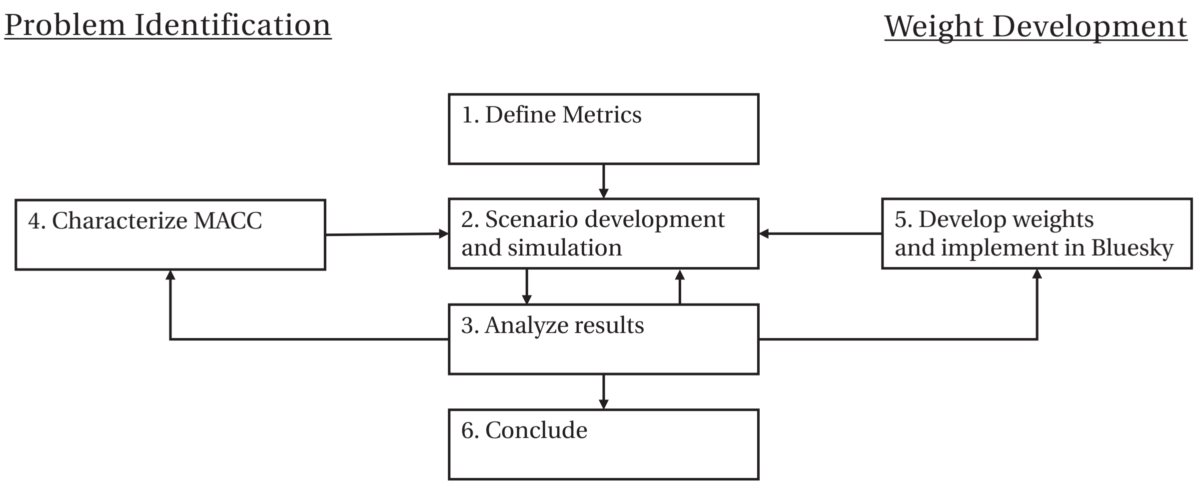


Figure 1.1: The workflow diagram of the research in this thesis

The six research activities in the workflow form the framework to reach this objective. Their content is further explained below, together with research questions for guidance

Research Activity 1
Define a set of metrics to characterize conflict resolution performance.
A set of metrics is developed to measure the performance of conflict resolution methods. The set of metrics should be able to describe multi-aircraft conflicts (MACC) and measure performance, both as stand-alone MACCs and in an environment with more traffic to analyze system or airspace level performance. This set of metrics drive the weight development and therefore need to be selected carefully. Answering the questions below will help define the set of metrics.

1. Which metrics are best suited to describe MACC resolution behaviour?
2. Which metrics are best suited to measure MACC resolution performance?

Research Activity 2
Develop and run experiment scenarios, to evaluate the effect of weighted and unweighted MVP algorithms on

MACC resolution performance.
The experiments serve to describe the performance and behaviour, in terms of the metrics defined in research activity 1, of multi-aircraft conflict resolution using the weighted and unweighted MVP algorithm. The exact activities performed vary per phase. First, the scenarios should increase the general understanding of solving MACC by the MVP algorithm, as well as the strengths and weaknesses. This knowledge should provide guidance to characterise MACC. In the second loop, after characterisation of the MACC, more detailed scenarios need to represent the categories In the round after the weights have been developed, they are tested on the already developed scenarios. It might be required to develop additional scenarios if the already existing scenarios are not adequate. Additionally, many-to-many scenarios need to be developed to give insights on the effects on a system level. The questions below are used to guide scenario development.

1. How can MACC resolution strengths and weaknesses be represented best in conflict resolution scenarios?
2. What set of conflict scenarios represent all categorised behavior?
3. What conflict scenarios represent free flight on a system level well?

Research Activity 3
Analyse and evaluate the experiment results
The experiment results need to be analysed after the simulations. The goal is twofold. First, it should be evaluated if the simulations provide the expected conflicts. In stand-alone MACC, the geometry in the simulation needs to equal the geometry on paper. In experiments in which many aircraft participate, the number of MACC and the geometry of the conflicts are subject to multiple factors like airspace density and heading distribution. In those cases, the contribution of MACC resolution and the type of MACC to the performance on a system level should be evaluated. Second, the results need to be understood thoroughly. The drivers of good and bad performance will serve as a corner stone for MACC characterisation and weight development. The questions below should assist in the analysis.

1. Do the scenarios provide the expected conflict situations?
2. Does the conflict resolution perform as expected?
3. How can the conflict resolution mechanics be explained?
4. What are the drivers of good or bad performance?
5. What metrics could be improved on?

Research Activity 4
Categorise A resolution behaviour
An infinite number of MACC can be created, although only a limited number of situations can be analysed. Therefore, the categorisation of MACC based on conflict geometry and resolution characteristics might offer a solution. Developing the right categories is key, as each conflict needs to be represented. When a set of conflicts is not well represented, the developed weights might not be well suited to solve those conflicts. On the other hand, when too many categories are developed, the desired simplification might not be reached. The questions below are used to guide the categorisation.

1. What conflict resolution mechanics can be categorised?
2. What conflict geometries show characteristic performance behaviour?

Research Activity 5
Develop weighting methods
Once the driving factors of inefficient conflict resolution are understood well, the insights gained should be used to develop a weighted sum of all individual conflict resolution vectors to improve the resolution performance. A weighting should not necessarily result in an improvement on each metric, a trade-off could be made to choose what metrics should be improved on. A weighting could also be used to show the potential gain in one metric at the cost of another, to get a better understanding of the possibilities. The questions below are used to guide the weight development.

1. On what metrics should the conflict resolution be improved?

2. Which variables are correlated with the metrics which should be improved?
3. What weight utilizes the correlation to improve performance?

Research Activity 6
Conclude on the opportunities to improve MACC resolution by weighting the individual conflict resolution maneuvers.
At last, the research should conclude on the opportunities to improve MACC resolution by weighting the individual conflict resolution maneuvers. Additionally, conclusions need to be drawn on the performance of the developed weights compared to the unweighted MVP algorithm.

1. What is the impact which weights have on A resolution?
2. How do the developed weights perform compared to the unweighted MVP algorithm?

1.2. Research Scope

In addition to the thesis object, questions, activities, and workflow, the project scope is structured and limited by the assumptions stated below.

The airspace is unmanaged
Aircraft will follow a direct route between the origin and destination, without the guidance of centralized air traffic management. To ensure safe flight, conflicts will be managed using decentralized conflict detection and resolution ($CD\&R$) methods.

Horizontal resolution only
Resolution activities will be limited to the 2D plane. This is in line with the previous assumption. Additionally, this is in line with previous research, Balasooriyan [1], Ribeiro et al. [15], Sunil et al. [20] so adhering to horizontal resolution makes the results better comparable.

Only enroute traffic at one flight level
All traffic will fly at the same flight level in experiments. Therefore, no CD&R will be performed as a result of altitude changes. This simplification with respect to the actual airspace is made as the research focuses on horizontal CR. Vertical maneuvers could induce short term conflicts.

All traffic in this simulation will participate in the conflict resolution at the same level
No distinction will be made on the contribution to conflict resolution per aircraft. Thus, all aircraft use the same conflict resolution and detection algorithms, without any set or randomized differences. Therefore, no rogue aircraft are simulated and the impact of human handling is neglected.

An ASAS time interval of $\Delta t = 1$ second is used.
The Airspace Separation Assurance System (ASAS) evaluates the near airspace for conflicts and calculates avoidance vectors for the conflicts at a fixed time interval. This interval is fixed for all aircraft and all simulations makes the mechanics of the developed methods better comparable. It should be noted that a one-second interval is easy to maintain in a simulation, but for a pilot it would be difficult to adjust the velocity and heading every second.

Improvement of multi-aircraft conflict resolution is limited to add weights to the pair-wise solution by the MVP algorithm
The further development of the MVP algorithm is limited to improving conflict resolution by adding weights to the currently pair-wise calculated weights. Other potential improvement noted during the research will be summarised in an advice for future research.

Weighting will not be communicated between aircraft
Aircraft will all use the same algorithm to determine the weights, but the determined weights will not be communicated between aircraft. This assumption is made as the MVP algorithm does also not use a line of communication to coordinate conflict resolution maneuvers.

Perfect ADS-B data is available
It is assumed that the data broadcast between aircraft is perfect. Therefore, the state date is continuously available without errors.

The effect of wind or turbulence on conflict resolution is neglected
The presence and therefore the effect of wind or turbulence on aircraft is omitted, as this would make understanding A resolution mechanics more difficult. When time permits, wind can easily be included in the simulation by enabling the Bluesky wind simulating module.

One aircraft type
All simulations will be performed using a Boeing 740-400. Thus, all aircraft will have the same performance limits, which makes it more manageable to analyze conflict resolution maneuvers. This type is also used in research by Ribeiro et al. [15], Balasooriyan [1], Sunil [18], which makes the results more comparable.

Look-ahead time of 300 seconds
A fixed look-ahead time of 300 seconds is used. This is a commonly used look-ahead time in. This look-ahead time is in line with the tactical maneuvers suggested by the MVP algorithm. It was found that this time is sufficient to identify and solve a conflict, Hoekstra et al. [8]

1.3. Preliminary Report Outline

In the remainder of this report, first, the existing literature about the concepts used in this research are discussed in chapter 2. Then, the mechanics of MACC will be investigated and subsequently MACC will be categorised in chapter 3. The knowledge gained will be used to develop a variety of weighting methods in chapter 4. Those methods will be tested in large-scale experiments developed in chapter 5. The experiment results are discussed in chapter 6, based on the results, a research plan for the second part of the thesis is suggested in chapter 7, the report is concluded in chapter 8

2

Literature Study

Increased environmental awareness and pressure on revenue systems in the aviation industry drives the desire to improve flight efficiency. The concept of free flights moves the responsibility of traffic separation away from the air traffic control towards the cockpit, allowing each aircraft to fly their direct route and reduce the distance flown. With an airborne separation assurance system aircraft ensure separation from other aircraft on board, since aircraft only need to be separated from other aircraft in their near region, the separation problem gets more clear. But to ensure safe self-separation future conflict needs to be detected and a resolution needs to be determined. This responsibility lies at the conflict detection, resolution and preventionmethods are explained in section 2.1. The Modified Voltage Potential (MVP) is such an algorithm developed to ensure this separation, based on the thought of charged particles which repel and keep separated in that way. This algorithm is at the basis of this research and will be explained in section 2.2. More insights in MACC mechanics can be gained using velocity obstacles as discussed in section 2.3. The last section will discuss the stability of airspace and the effects conflict resolution algorithms have on it, section 2.4. The existing literature discussed in this chapter are about concepts which are used throughout this thesis research.

2.1. Conflict Detection, Resolution and Prevention

The opportunity for aircraft to fly direct routes as part of the free flight concept, can only be realised when self-separation can be assured. To do so, potentially dangerous situations first need to be recognized and subsequently avoided. This section will elaborate on the concepts which provide this information. First, conflict detection (CD) is discussed in section 2.1.1, then conflict resolution (CR) is discussed in section 2.1.2 and conflict prevention (CP) is discussed in section 2.1.3.

2.1.1. Conflict Detection

The goal of conflict detection algorithms is to predict future loss of separation (LoS). A LoS occurs when two aircraft violate the separation criteria, by entering the area of clearance around another aircraft. This area is called the protected zone (PZ) and is defined as a disk with radius r_{pz}, which equals a minimum separation distance d_{PZ} of 5 NM in the horizontal direction and a distance of 1000 ft up and down from the aircraft, [10]. Most CD algorithms are limited to a set look-ahead distance d_{LA} or time t_{LA} and extrapolate the state data of itself and the aircraft within those limits to predict LoS.

Types of Surveillance

The state data used in CD&R can be retrieved from various surveillance systems, Jenie et al. [11] distinguished three categories: independent surveillance centralized-dependent surveillance, and distributed-dependent surveillance systems. Conflict detection is as good as the data recieved. Therefore, it is crucial to gain data through the system which is most appropriate for the selected conflict detection and resolution method.

In independent surveillance, data is gained using on-board sensors. In manned flight, this type of surveillance is limited to see and avoid procedures based on human visuals. This type of surveillance is more popular in the UAV domain. In centralized-dependent surveillance, data is retrieved from a centralized station-network. The data can include both static and dynamic data. The static data, like terrain and weather, can be available already before departure. In distributed-dependent surveillance, data is sent from and retrieved by traffic itself. Therefore, all traffic in the system is required to participate in cooperative broadcasting of flight data. Currently, manned flight uses the Automatic Dependent Surveillance Broadcast (ADS-B).

State propagation
After the state data is received, it needs to be propagated to detect conflicts. Various propagation methods exist, Kuchar and Yang [12] made a categorisation of three approaches to extrapolate the received state data: nominal, worst-case, and probabilistic. Per approach, it varies which conflicts are detected and at what moment they are detected. Therefore, the extrapolation approach has a large influence on conflict detection methods.

The nominal method is the most simple, the current states are directly extrapolated without considering uncertainties. On the other end, the state data can be extrapolated using a worst-case projection which accounts for any possible range of maneuvers. When any of the maneuvers in this range causes a conflict, the aircraft are in conflict. The probabilistic model is the most complex, as it describes potential variations in the future trajectory of an aircraft by modeling uncertainties. Where the nominal method might detect some conflicts at a later stage due to the lack of any uncertainty modeling and the worst-case method might predict too many conflicts creating an unworkable situation, the probabilistic method lies in between. Although, predicting an aircraft path comes with challenges as well.

2.1.2. Conflict Resolution
Conflict resolution is the act of finding a path free of detected conflicts, by adjusting heading, velocity or altitude. Various methods have been developed in this field. In addition to surveillance systems, Jenie et al. [11] also described coordination, maneuver, and autonomy as part of the taxonomy of CD&R approaches. In all categories, different system types were identified.

Types of Coordination
As part of the conflict resolution categorisation, three types of coordination are differentiated: explicitly coordinated avoidance, implicitly coordinated avoidance, and uncoordinated avoidance. In explicitly coordinated avoidance, resolution maneuvers are communicated among the involved aircraft. The explicit communication provides the opportunity to negotiate a specific solution. In implicitly coordinated avoidance, the resolution maneuvers are determined by each aircraft individually using a common strategy or rule set. This does not require the need of communication for resolution. In uncoordinated avoidance, each aircraft determines its own preferred resolution and executes it without communicating. As this might lead to dangerous and complex situations, this type of coordination is rarely used.

Types of Avoidance Maneuver
As part of the conflict resolution categorisation, three types of maneuvers are differentiated: strategic, tactical, and escape maneuvers. In those types, the strategic maneuver is initialised far before paths would be crossed. This long-range maneuver causes a significant deviation from the flight plan to avoid conflicts. The tactical maneuver is initialised closer to a potential LoS. This mid-range maneuver aims to keep the path deviation small. The escape maneuver is initialised when the aircraft are already close. It is an aggressive maneuver with the sole intention to prevent a collision.

Types of Autonomy
Last, the level of autonomy is distinguished. After determining the resolution maneuver to solve a conflict, this maneuver needs to be executed. This could be done either manually or autonomously. If it is done manually, the resolution maneuver is suggested to a human operator which then has the final call for the avoidance measures. An autonomous system does not have the human intervention, but will execute the maneuver itself. Safety regulations prevent the implementation of those autonomous systems in manned aviation.

2.1.3. Conflict Prevention
Conflict prevention algorithms have the goal to assist pilots in preventing conflicts from happening in the first place Rand and Eby [14]. It propagates velocity, heading, altitude, rate of climb and rate of turn of the own aircraft and detects what trajectory changes lead to a conflict.

Conflict prevention will not be actively used in the thesis work presented, although understanding the principle well may contribute to conclusions drawn and future recommendations.

2.2. Modified Voltage Potential

A force field based CR algorithm was first developed by Eby [2]. The basics of his idea lies in the principle of charged particles which repel when getting close to each other. Eby suggested a tactical maneuver, where the velocity and heading change would ensure separation, while route deviations are only small. The algorithm was modified by Hoekstra et al. [7] and renamed to Modified Voltage Potential (MVP), as part of a larger study in the development of the free flight concept.

The MVP algorithm uses a state-based CD module and force field based CR. Which together are part of the Airborne Separation Assurance System (ASAS). This system provides the pilots with information about detected conflicts and suggested resolution maneuvers to maintain situational awareness. In the study by Hoekstra et al., it was noticed that a maneuver to solve a conflict could lead to a potentially dangerous short-term conflict. To prevent those situations, the predictive ASAS (PASAS) module was developed. This module detects which conflict resolution maneuvers lead to new conflicts and presents this to the pilots. The pilots can use this information to choose which maneuver to make.

The conflict detection module uses the aircraft state data to determine if the aircraft itself, called the ownship, is in conflict with other aircraft, called intruders. The state data is received through an ADS-B system, as part of a distributed-dependent surveillance system. No intend information is used and it is assumed that the aircraft will not change its velocity or heading within the look-ahead time, so a nominal state propagation method is used. The velocity vector is used to extrapolate the current location to an estimated path. Then the time to the closest point of approach t_{CPA} between both aircraft is calculated using eq. (2.1), here $d_{O,I}$ is the distance between the ownship and the intruder. When the distance at the closest point of approach d_{CPA} between both aircraft is smaller than the protected zone radius r_{PZ}, a LoS is predicted and the aircraft are in conflict. The distance vector $\mathbf{d}_{CPA}$ between both aircraft can be found using eq. (2.2). When aircraft do not fly at the same altitude, the separation can also be ensured vertically. Aircraft are then only in conflict when the horizontal and vertical separation minima are both violated at the same time, as the scope of the current research is limited to horizontal flight, vertical separation will not be further detailed here. For more information about the combination of horizontal and vertical separation, the reader is referred to Hoekstra et al. [7].

$$t_{CPA} = -\frac{\mathbf{d}_{O,I} \cdot \mathbf{v}_{rel}}{\mathbf{v}_{rel} \cdot \mathbf{v}_{rel}} \tag{2.1}$$

$$\mathbf{d}_{CPA} = t_{CPA} \cdot \mathbf{v}_{rel} - \mathbf{d}_{O,I} \tag{2.2}$$

The computation of the avoidance vector dv is further explained with the help of the conflict situation in fig. 2.1. The horizontal intrusion d_i is calculated by subtracting d_{CPA} from r_{PZ}. A change in velocity **dv** in the direction of $\mathbf{d}_{CPA}$ is calculated to ensure that the closest point of approach CPA is outside the PZ, i.e., a deviation d_i from the path is needed at t_{CPA}. However, if the d_{CPA} is moved in the $\mathbf{d}_{CPA}$ direction until the PZ border, a new CPA would still be in the protected zone, as is shown infig. 2.1, here v_{sol^*} is the solution without correction. The new CPA should instead lie on the PZ border to prevent a LoS, therefore a corrected horizontal intrusion $d_{i,corr}$ is calculated using eq. (2.3). The required change in velocity **dv** to solve the conflict is now calculated using eq. (2.4). The required velocity change is then added to the current velocity vector to find the solution $\mathbf{v}_{sol}$. The solution found grazes the intruders protected zone. Additionally, a margin could be added to the protected zone to reduce the possibility of a LoS and increase safety.

$$\frac{d_i}{d_{i,corr}} = \left| cos\left(arcsin\left(\frac{r_{PZ}}{d_{O,I}}\right) - arcsin\left(\frac{d_{CPA}}{d_{O,I}}\right)\right)\right| \tag{2.3}$$

$$\mathbf{dv} = \frac{d_{i,corr}}{t_{CPA}} \cdot \frac{\mathbf{d}_{CPA}}{d_{CPA}} \tag{2.4}$$

The geometry of this solution ensures that the avoidance vectors for both aircraft are the same, but opposite. Thus, the conflict will be solved by both aircraft at the same time. Therefore, the conflict would also be solved when the conflict resolution of one aircraft fails. In reality, it can occur that the pilot of one aircraft reacts to

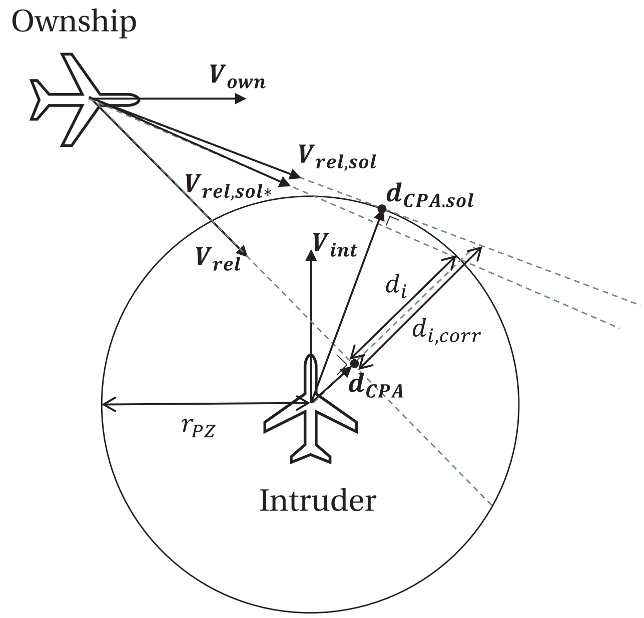


Figure 2.1: Conflict resolution using the MVP algorithm.

the advised conflict resolution and full executes it before the pilots of the other aircraft do. In this case, the conflict is also solved by one aircraft.

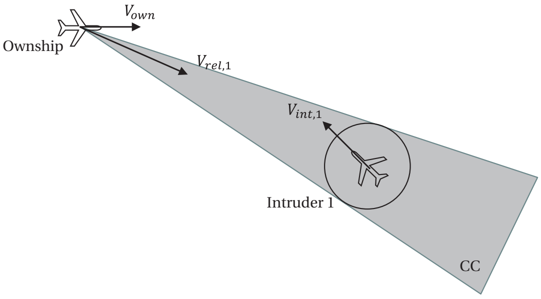
Once a conflict-free path is found, it will be followed until the CPA is passed. If the aircraft is involved in multiple conflicts, the conflict fee path has to be followed until all CPAs are passed. After that, the aircraft can revert back to the next waypoint on its route or to the original heading if there are no way points planned.

The avoidance vector **dv** is calculated for each conflict separately. When an aircraft conflicts with multiple aircraft at at once, all **dv** are summed in line with the voltage potential analogy. Indeed, this sum will not lead to a path grazing the protected zone of the intruders and even does not directly solve all MACC situations, for those cases iterations are needed to find a conflict-free solution, as will be explained in chapter 3. To improve solving MACC, it can be beneficial to add weights to the pairwise calculated **dv** before summing them, as will be investigated in this thesis.

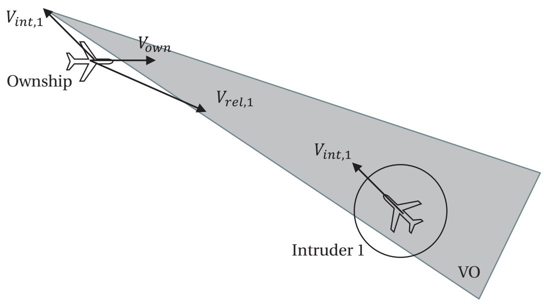
2.3. Velocity Obstacles

A widely used concept in conflict detection and resolution, both in robotics and aviation are velocity obstacles. The concept was first defined by Tychonievich et al. [21] and called avoidance cones. It was used as an approach to find a conflict free path in a 2 dimensional path planning problem with moving obstacles. Fiorini and Shiller [4, 5] further investigated motion planning in dynamic environments and started using the name velocity obstacles instead of avoidance cones.

The velocity obstacle (VO) is the set of velocities for which an aircraft will, at some point in time, cross the protected zone of another aircraft, assuming that the other aircraft will keep a constant velocity and heading. A velocity obstacle is composed of aircraft position, velocity, and protected zone radius. First, the collision cone is constructed. The collision cone represents the set of all relative velocities which will cause a loss of separation, geometrically this set can be described as the set of velocities which are between the two relative velocities which start from the ownship and are tangent to the protected zone of the intruder. The velocity obstacle is then constructed by translating the collision cone by the velocity of the intruder, as shown in fig. 2.2. This velocity obstacle represents the set of velocities for the ownship which will lead to a LoS, assuming that the intruder velocity and heading will remain constant. The velocity vectors constructing the border of the VO, represent solutions where the ownship will graze along the intruder its protected zone. If the ownship is in conflict with multiple intruders, the set of velocity vectors leading to a LoS is the union of the velocity obstacles of all pair-wise conflicts, as shown in fig. 2.3a.



(a) The collision cone (CC) from the ownship to intruder 1 is composed by the the lines tangent to the PZ of intruder 1 which originate at the ownship.

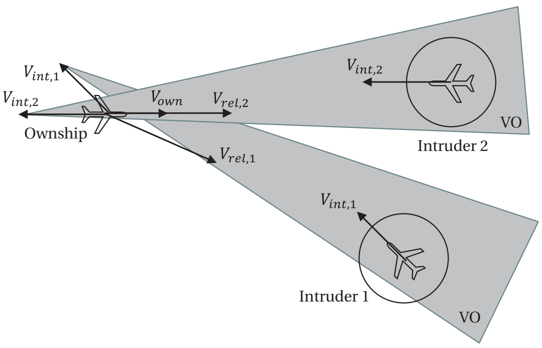


(b) The velocity obstacle (VO) from the ownship to intruder 1 is composed by translating the CC with the velocity of intruder 1 $v_{int,1}$

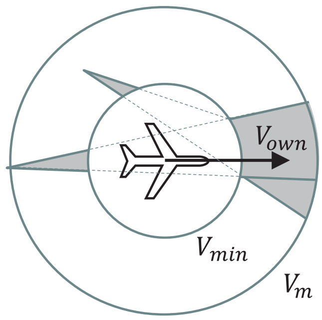
Figure 2.2: The collision cone and velocity obstacle for the ownship in conflict with intruder 1

2.3.1. Solution Space Diagram

When combining the velocity obstacles with the aircraft speed limits, an intuitive interface showing possible solutions is created, as shown in fig. 2.3b. This was first conceptualized by Hermes et al. [6] and called the Solution Space Diagram (SSD). The SSD is a useful tool when analyzing conflicts and conflict resolution methods. It clearly indicates the conflict free velocities and when a solution is found far from the border, it is clear that smaller velocity changes would also solve the conflicts. The downside of this method is that only instantaneous solutions can be found, where the ownship is required to fully solve the conflict. There may be more solutions available when relying on partial conflict resolution of the intruders, as will be discussed in section 3.4.1.



(a) The velocity obstacles from the ownship to intruder 1 and intruder 2, the union of both VO form the set of velocities for the ownship which lead to a LoS.



(b) The SSD of the conflict shown in fig. 2.3a for the ownship is composed by combining the velocity obstacles with the velocity limits of the aircraft.

Figure 2.3: The velocity obstacles and SSD for the ownship in conflict with intruder 1 and intruder 2

2.4. Airspace Stability

The number of aircraft which can fly in an airspace while maintaining safe separation is limited. In free flight, the factors effecting the maximum density are the area of the protected zone and the area needed to prevent LoS. Sunil et al. [20] have done elaborate research into the effect of conflict detection and resolution on airspace stability and capacity. This section will first introduce a key concept in capacity and stability modeling, the domino effect parameter (DEP) in section 2.4.1. Then the effect of CD&R on the airspace capacity will be discussed in section 2.4.2.

2.4.1. Domino Effect Parameter

Conflict resolution maneuvers can lead to new conflicts or even to new conflict chains. The airspace stability is related to the conflicts occurring as a result of conflict resolution. The airspace stability can be measured using the DEP, which is the proportion of destabilizing conflicts. The DEP can be determined from a simulation, using the ratio of the number of conflicts when conflict resolution is used $C_{total_{wr}}$ and the number of conflicts when no conflict resolution algorithm is used $C_{total_{nr}}$ in the same scenario, as shown in eq. (2.5).

$$DEP = \frac{C_{total_{wr}}}{C_{total_{nr}}} - 1 \tag{2.5}$$

2.4.2. Effect of Conflict Detection and Resolution on stability

When an aircraft follows a straight path, the possibility of conflict increases with an increased path length as every predefined timestep the CD module analyses the area within the look-ahead time for conflict. Due to aircraft movement, this area is slightly moves each time step and new intruders can enter the area within the look-ahead time. Path deviation due to CR causes a larger distance flown and increased flight time, therefore increased distance searched for conflicts k_{CR} and increased chance of conflict. Since only small path deviations resulting from CR maneuvers using MVP, Sunil et al. [20] assumed that the aircraft do not recover to the original path after conflict resolution, instead the aircraft fly a trajectory parallel to the original path. The k_{CR} can now be calculated using eq. (2.6), with $\mathbf{v}_0$ the velocity at the conflict start and $\mathbf{v}_s ol$ the conflict free velocity. The dependence of k_{CR} on the conflict angle θ and d_{CPA} is visualized in fig. 2.4. Smaller conflict angles and larger intrusions cause a larger k_{cr}. Additionally, the CR maneuver will cause the conflict detection module to evaluate part of the airspace which it will not be crossed, as visualised in fig. 2.5 . The extra distance evaluated by the CD module k_{CD} can be calculated using eq. (2.7). Combining k_{CR} and k_{CD} gives the extra distance searched for conflicts due to CD&R k_{CDR}, as shown in eq. (2.8). A lower k_{cdr} will result in a lower number of conflicts due to CD&R and thus a lower DEP. Airspace stability can therefore be increased by reduced heading changes to reduce k_{CD} and by reduced path deviation to reduce k_{CR}. The largest effect comes from k_{CD}. To illustrate, k_{CD} is 41.7 nm for a 300 second t_{CPA} and a v_0 of 500 Kts, which is much larger than the k_{CR} shown in fig. 2.4, it should be noted that the d_{sep} used in the research presented in this thesis is twice the size of the d_{sep} used for the calculations by Sunil in the figure.

$$k_{cr}(\theta, d_{CPA}) = |\mathbf{v}_{sol}|t_{CPA} - |\mathbf{v}_0|t_{CPA} \tag{2.6}$$

$$k_{cd} = |\mathbf{v}_0|t_{LA} \tag{2.7}$$

$$k_{cdr} = k_{cd} + k_{cr} \tag{2.8}$$

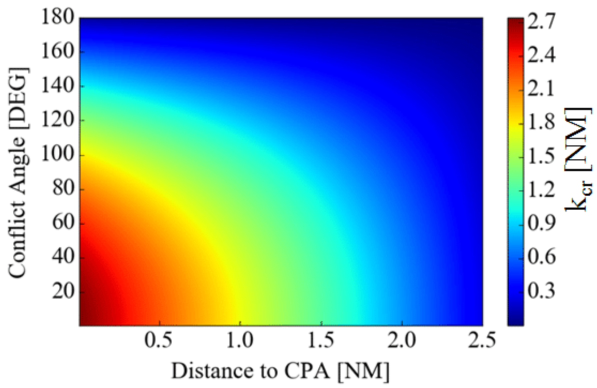


Figure 2.4: Extra distance searched due to conflict resolution by MVP for d_{sep} = 2.5 nautical miles , t_{LA} = 300 s, and v_0 = 500 kts, by Sunil et al. [20]

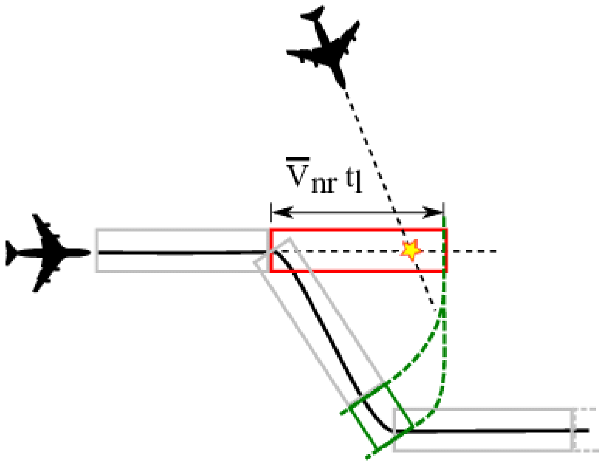


Figure 2.5: The total area searched for conflicts is increased due to conflict detection (red) and conflict resolution (green). Figure by [20].

3
Mechanics and Characterisation of multi-aircraft Conflict Resolution

In this chapter, efforts are made to explain the conflict resolution mechanics of multi-aircraft conflicts. First a set of measures to define good or bad performance is defined in section 3.1. Then the set of solutions and the effect of iterations is discussed in section 3.2 and section 3.3, respectively. Then the mechanics will be used in the categorisation and explanation of MACC resolution in section 3.4. The findings will be concluded in **??**

Conflicts and conflict resolution in this section and the next sections will be often explained from the perspective of an aircraft as an autonomous agent. In reality, a resolution vector will be calculated using an algorithm and advised by the ASAS. The advice needs to be executed by the pilot or auto-pilot before a conflict is resolved. In the simulations in this research, the calculated resolution is directly executed, therefore it is said that an aircraft solves the conflict. In the more thorough conflict analysis, the situation is analyzed from the perspective of one of the aircraft involved in the conflict. This aircraft is then called ownship, and the other aircraft involved are called intruders. A conflict between the ownship and intruder 1 is called conflict 1, a conflict between the ownship and intruder 2 is called conflict 2, a conflict between intruder 1 and intruder 2 is conflict 1-2. Furthermore, the avoidance vector and relative velocity for conflict 1 are referred to as dv_1 and $v_{rel,1}$

3.1. Multi Aircraft Conflict Resolution Measures

Before analyzing MACC mechanics, it is useful to determine based on what metrics the conflict resolution method will perform good or bad. Most important is that conflict resolution ensure safe separation. Additionally, one could look at the airspace stability by measuring the DEP as discussed in section 2.4. However, in this chapter the MACC will be analysed without considering traffic which is not involved in the conflict, so the MACC resolution is analysed as stand-alone conflicts. Therefore, no secondary conflicts will be induced due to conflict resolution.

The deviation of the conflict could however be analysed, this is an important metric as it is desired to have low path deviation to decrease the distance flown and therefore fuel burned. Additionally, a larger deviation would lead to larger possibility of extra conflicts in a situation where more traffic is present. The deviation is defined as the distance between the position of the aircraft after the conflict is solved $\mathbf{POS}_{t=t_{conf,WR}}$ and the expected position of the aircraft at the same time in case of no conflict resolution $\mathbf{POS}_{t=t_{conf,NR}}$, as shown in fig. 3.1. $\mathbf{POS}_{t=t_{conf,NR}}$ is calculated by nominal extrapolation of the aircraft velocity before the conflict starts $\mathbf{v}_0$ for a period $t_{conf,NR}$.

From the figure it becomes clear that a larger heading change would lead to a larger deviation, therefore a small heading change is beneficial. Thus, the heading change needed to solve a conflict might give useful insights in the deviation, especially when comparing conflict resolution of various methods on the same conflict. The heading change over time can provide additional insights. A constant heading change suggests a smoother conflict resolution maneuver, compared to a varying heading changes in a short period. This

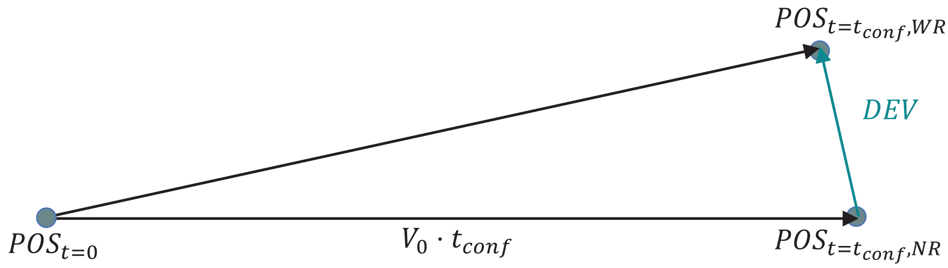


Figure 3.1: The definition of deviation used in this research

indicates a more comfortable maneuver. Also strong variation in heading changes will increase the distance searched for extra conflicts by the conflict detection module k_{cd}, as explained in section 2.4.
In addition, the time needed to solve a conflict is measured. Faster conflict resolution ensures that the aircraft find a conflict free trajectory sooner and is therefore beneficial.

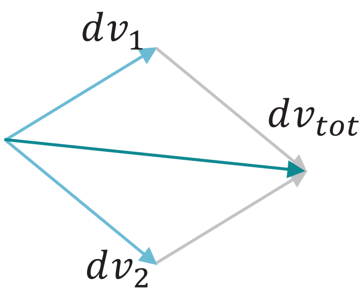
To summarize, in the conflict resolution analysis of this thesis the heading change of aircraft will be consulted as it gives an indication of the aircraft deviation and the smoothness of the solution. Additionally the heading change will stop when a conflict free path is found, so it also indicates the conflict duration.

3.2. The set of weighted velocity change vectors in a MACC

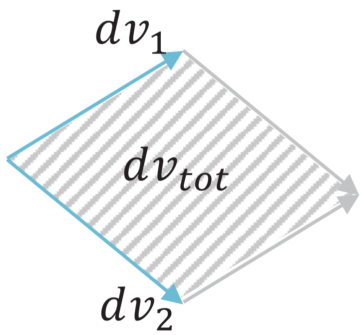
To better understand the potential of weights, consider a situation where the ownship is in conflict with intruder 1 and intruder 2, the unweighted MVP algorithm calculates the velocity change $\mathbf{dv}_{tot}$ as the sum of the pair-wise velocity changes, as shown in eq. (3.1) and visualized by fig. 3.2a. When the pair-wise **dv** are weighted, $\mathbf{dv}_{tot}$ can be calculated using eq. (3.2). Now a set of velocity changes becomes available. This set is shown in fig. 3.2b for all weights w between zero and one. It should be noted that those effects only occur when the ownship is in conflict with multiple intruders at the same time, i.e. multiple pair-wise **dv** are calculated at the exact same moment. The remainder of this chapter will further elaborate on the possibilities which come with including weights, based on a simple categorisation made in section 3.4

$$\mathbf{dv}_{tot} = \mathbf{dv}_1 + \mathbf{dv}_2 \tag{3.1}$$

$$\mathbf{dv}_{tot} = w_1\mathbf{dv}_1 + w_2\mathbf{dv}_2 \tag{3.2}$$



(a) The sum of the pair-wise **dv** in a MACC result in the suggested velocity change vector $\mathbf{dv}_{tot}$ for the unweighted MVP algorithm.



(b) The sum of the pair-wise **dv** in a MACC result in the suggested velocity change vector $\mathbf{dv}_{tot}$ for the unweighted MVP algorithm.

Figure 3.2: The $\mathbf{dv}_{tot}$ in MACC for the unweighted MVP algorithm and the set of $\mathbf{dv}_{tot}$ for the weighted algorithm with weights between zero and one.

3.3. Iterative conflict resolution

In the simulations in this research, the conflict detection and resolution algorithms almost continuously evaluate and resolve conflicts, i.e., every time step it is redetermined which aircraft are in conflict and which avoidance vectors would solve the conflict according to the MVP algorithm. An ASAS time step used is 1 second. The heading and velocity change made in 1 second is limited by the aircraft physics and is often not large enough to fully carry out the conflict resolution and to solve a conflict. To illustrate, the maximum heading change of a Boeing 740-400 in 1 second in Bluesky is about 1 degree, its velocity change is 0.5 m/s . So, every time step the conflict is reevaluated and the avoidance vector is recalculated until the aircraft are conflict free. The iterative solving is illustrated by solving the simple head-on conflict as shown in fig. 3.3. For this example it is assumed that the intruder will not contribute to the conflict resolution. The iterations needed to solve this conflict are shown in fig. 3.4. This example shows that the ownship did not fully complete the suggested resolution at the first iteration. The slight rotation of dv results in a slightly different solution $v_{sol,it}$ compared to the instantaneous solution $v_{sol,inst}$. This rotation is the result of a rotation in the relative velocity due to conflict resolution. This iterative solving of conflicts does not cause large differences with respect to an instantaneous conflict resolution, when only one aircraft participates in the conflict resolution. When both aircraft would participate the avoidance vector completed would be half of the initially calculated avoidance vector, for both aircraft. The effect of itterataions on MACC might be larger, as explained in section 3.4.

In the simulations, heading and velocity are almost continuously adapted to the conflicts. This is done for all aircraft at the same time. When an ASAS system would be on board, where pilots need to carry out the suggested maneuver, it would not be possible to perform this conflict resolution so accurately and at the exact same time for all aircraft. The time step on board would be larger and the conflicts would be evaluated less often to ensure its manageability by pilots. Therefore, the solutions would be closer to the instantaneous conflict resolution, compared to the small time step.

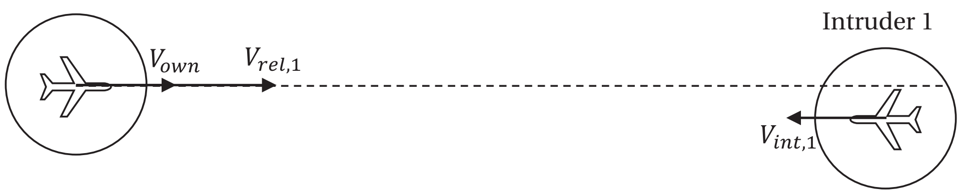


Figure 3.3: Head-on conflict between the ownship and intruder 1. The circles around the aircraft represent their protected zone. The dotted line is the path of the ownship in case of no conflict resolution.

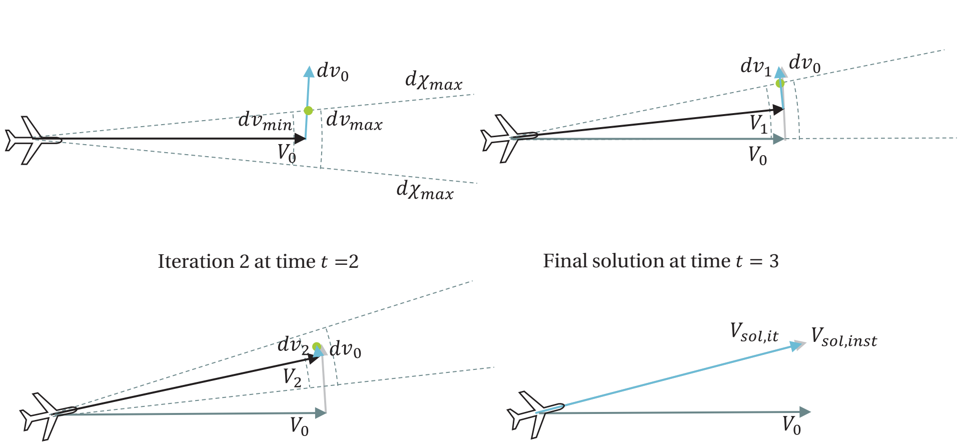


Figure 3.4: Iterative conflict resolution of the ownship in conflict fig. 3.3. The first figure shows its initial velocity v_0 and resolution calculated by the MVP algorithm dv_0, the dotted lines are the heading and velocity change limits within one time step due to physical restraints. The second and third picture show the situation after one and two iterations respectively and compares it to the initial condition. The final figure shows a slight deviation in the iterative solution $v_{sol,it}$ compared to the instantaneous solution $v_{sol,inst}$

3.4. Oversolving and Undersolving

When the ownship is in conflict with multiple intruders, a categorisation in conflict geometry can be made based on the direction of the pair-wise avoidance vectors. Here, the heading changes are distinguished in two groups, one for each side of the aircraft. Thus all heading changes causing a turn to the left are on one side and all heading changes causing a turn to the right are on the other side.

When all vectors suggest a maneuver to the same side, the maneuvering direction is clear, although there will be a risk of making a maneuver which is to big, as explained in section 3.4.1. When the heading changes to opposite sides are suggested, the solution is less obvious and will not directly be found, as explained in section 3.4.2. The situations discussed in this chapter are limited to two intruders, but are, to some extend, also applicable to situations involving more aircraft.

3.4.1. Oversolving

Consider the case where the pair-wise conflict resolution of all intruders requires the ownship to make a heading change to the same side, like the example in fig. 3.5 shows. In the SSD of this situation as shown in fig. 3.6, it can be seen that the unweighted sum resolves the conflict by directing the ownship into the conflict free space, when the conflict resolution is completed instantaneous. Although this maneuver would directly resolve all conflicts, the maneuver made is larger than necessary. The conflicts are already solved when $\mathbf{v}_{sol}$ is at the border of the velocity obstacles. A larger maneuver would not further solve the conflict and could therefore be seen as unnecessary and inefficient. One could say that the ownship keeps maneuvering after it already is on a conflict free path. This is called oversolving. A more efficient solution is found closer to the border of the SSD.

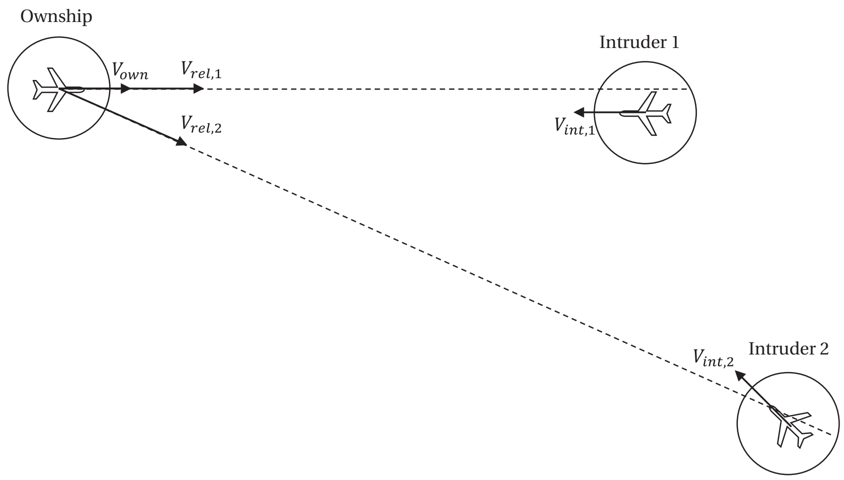


Figure 3.5: Conflict geometry of conflict situation 1. This conflict will lead to oversolving of the ownship

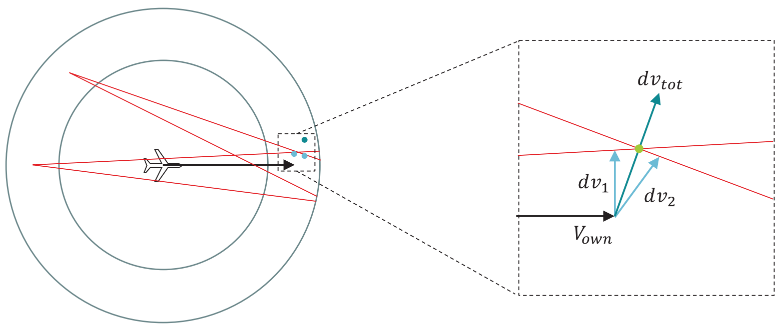


Figure 3.6: The ownship SSD of the conflict shown in fig. 3.5. All velocities outside the red borders will result in a conflict free situation. The magnification shows that the total $\mathbf{dv}_{tot}$ passes the SSD border far beyond, so the conflict resolution suggested is larger than necessary. This conflict is oversolved by the ownship.

Now, consider the case where conflicts are iteratively solved, as is shown in fig. 3.7. When the time step is large enough to fully carry out the advised resolution, the overshooting would be the same size as without iteration. When the time step is small, as the time step used in this research, the amount of overshooting will be reduced. After each iteration, the amount of overshooting will be reduced as the sum of **dv** will be reduced. The overshooting will however not be fully dissolved. When the aircraft reaches a conflict free path, no new conflict resolution vector will be calculated, but the last found solution will be fully completed. Thus, the total overshooting depends on the last calculated $\mathbf{dv}_{tot}$. Therefore, smaller time steps reduce oversolving. Although oversolving will not not fully be dissolved as shown in the figure. The potential improvements between the border and iterative resolution are small, although present. This effect is well seen when looking at the flown path in fig. 3.8 and heading changes in fig. 3.9 of the aircraft when solving the conflict instantaneous or using a small time step. Solving the conflicts sequentially, by prioritizing one of the conflicts over the other, will prevent overshooting as at no point the sum of both **dv** will be used as a solution. The potential improvements between the border and instantaneous resolution are large. Therefore, small improvements in simulations could have a big impact when used on board.

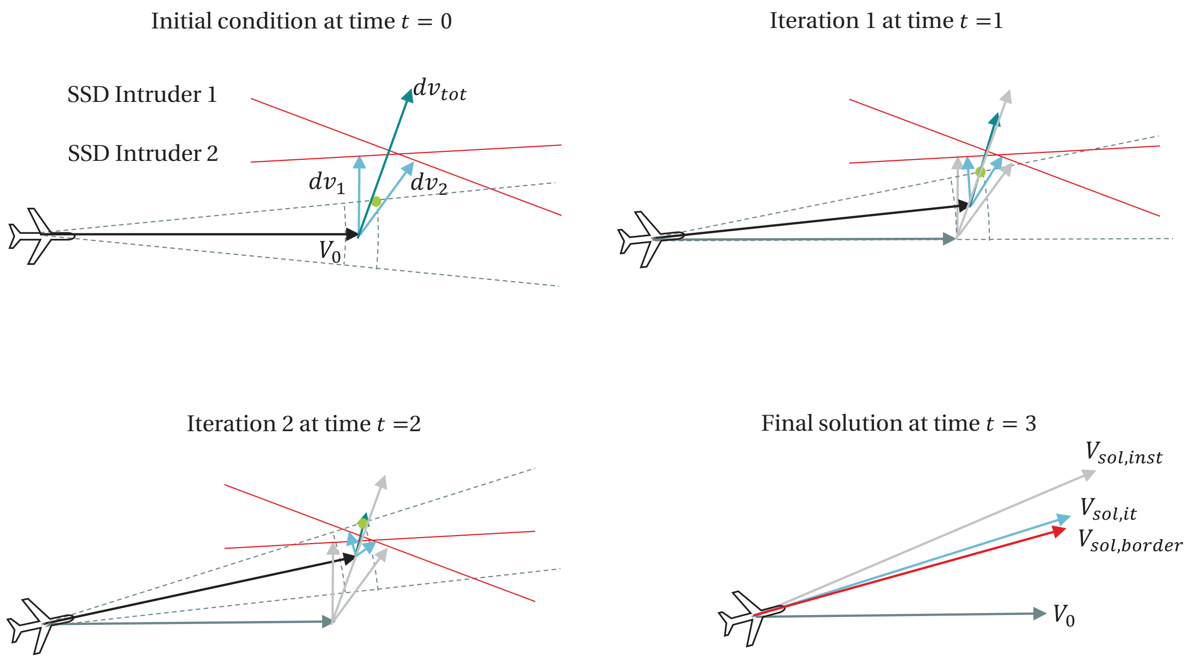
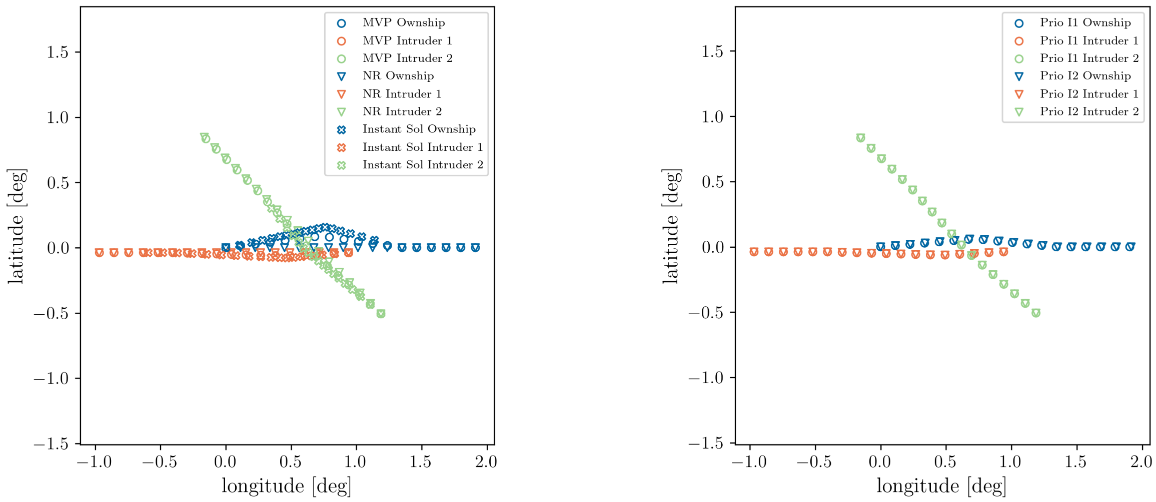


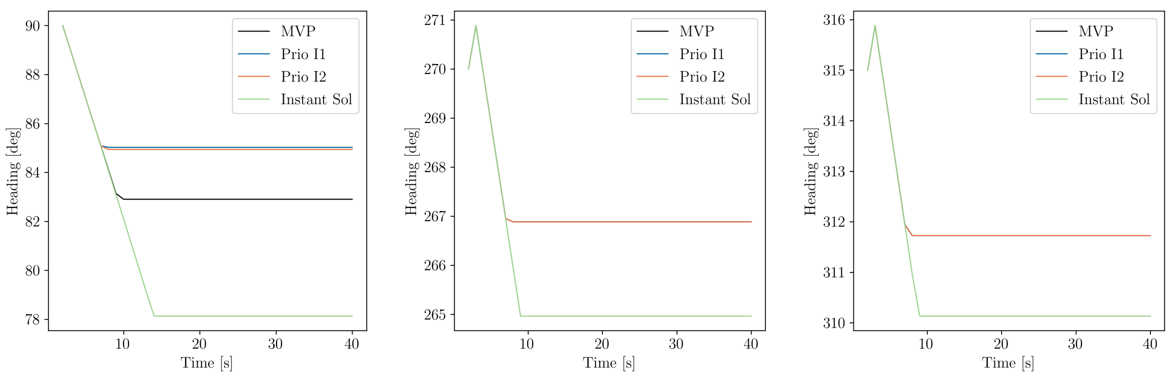
Figure 3.7: Iterative conflict resolution of the ownship in conflict fig. 3.5. The first figure shows its initial velocity v_0 and resolution calculated by the MVP algorithm dv_0, the dotted lines are the heading and velocity change limits within one time step due to physical restraints. The second and third picture show the situation after one and two iterations respectively and compares it to the initial condition. The final figure shows a large deviation in the iterative solution $v_{sol,it}$ compared to the instantaneous solution $v_{sol,inst}$ and the border solution $v_{sol,border}$



(a) Significant path deviation for the instantaneous solution compared to the planned path is reduced by iterating with a 1 second time step.

(b) Prioritizing one conflict over the other further decreases the path deviation as there will not be any overshooting.

Figure 3.8: Aircraft path using various conflict resolution to solve conflict fig. 3.10.



(a) Ownship heading over time

(b) Intruder 1 heading over time two.

(c) Intruder 2 heading over time

Figure 3.9: Heading over time of the aircraft involved in conflict fig. 3.5, when solving the conflict using the unweighted MVP algorithm with a one second time step, the unweighted MVP solution, fully prioritizing the conflict with aircraft 1 and fully prioritizing the conflict with aircraft 2. A small time step reduces overshoot, but does not dissolve it. Prioritizing one solution will prevent overshooting.

3.4.2. Undersolving

Consider the case where the pair-wise avoidance vectors of the intruders requires heading changes in opposite directions, like the example in fig. 3.10 shows. Here, the pair-wise vectors are counteracting. When looking at the SSD in fig. 3.11, it can be clearly seen that the sum of the pair-wise vectors does not resolve any conflict. In this case, the sum of the avoidance vectors does not directly maneuver the ownship to a conflict free trajectory. The conflicts will only be solved after multiple iterations and rely on the maneuvering of all aircraft. The case where the summed conflict resolution vector stays inside the velocity obstacles is called undersolving.

In cases of undersolving, iterative solving is crucial for the MVP algorithm, especially when the intruders are also involved in other conflicts which cannot be solved directly. In those cases, the suggested conflict resolution of neither the intruders nor the ownship would solve the conflicts. Due to the iterations, the aircraft and therefore the conflicts would expand and a passage would be created. This iterative conflict resolution offers opportunities which are not seen on the SSD, but might be more efficient. Therefore, iterative conflict resolution is beneficial both in conflicts which would be oversolved and undersolved when solved instantaneously. When a larger time step would be chosen in a simulation or on-board, the reduced iterative behaviour should be accounted for. In this subsection, two conflict situations are used to illustrate the oversolving behaviour.

Conflict situation 2

Although iterations drive the unweighted MVP algorithm to a more efficient solution than other algorithms find, there might be improvements possible in some cases. Consider conflict situation 2 as shown in fig. 3.10, the SSD of the ownship can be found in fig. 3.11. The heading during conflict resolution of the aircraft involved in this situation gives insight in the iterative conflict resolution and is shown in fig. 3.12. In this situation, the absolute value of $\mathbf{dv}_1$ is larger than the absolute value of $\mathbf{dv}_2$, therefore $\mathbf{dv}_{tot}$ suggests a maneuver which will contribute to resolving the conflict with intruder 1, but will counteract the resolution efforts of intruder 2. As long as $\mathbf{dv}_{tot}$ and $\mathbf{dv}_2$ are outside the time step maneuvering limits, both aircraft will maneuver in the same rate in the same direction, which does not solve the conflict of these aircraft but does solve the conflict between the ownship and intruder 1. Solving conflict 1 will decrease the intrusion and therefore decrease the absolute value of $\mathbf{dv}_1$. After nine seconds, $\mathbf{dv}_1$ and $\mathbf{dv}_2$ become similar in size, $\mathbf{dv}_{tot}$ will be in the maneuvering limits of the ownship. The moderate maneuvering ensures that dv_{tot} stays within the limits until one of the conflicts is solved. After that a small zigzag in heading is visible, this is the result of sequentially solving conflicts with intruder 2 and intruder 1.

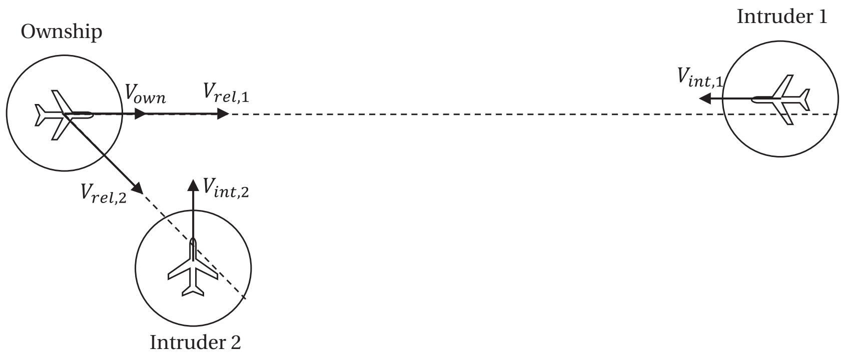


Figure 3.10: Conflict situation 2. The conflict geometry leads to undersolving of the ownship

The conflict resolution is dominated by the largest dv, dv_1 in this case, i.e., the path deviation of the ownship is in the direction of the dominant dv. The direction in which a conflict is solved is a function of t_{LOS} and d_I, as the dv is a function of those variables. Both variables are an indication of how severe a conflict is. Thus, implicitly more severe conflicts are prioritized in a multi-aircraft conflict. However, one could wonder if this implicit relation is the best one to prioritize conflicts in terms of safety, efficiency, or stability.

fig. 3.13a shows the path aircraft follow during conflict resolution significantly deviates from their original path. As conflict 1 has both a high intrusion and a small time to LoS, a large heading change seems inevitable. Conflict 2 on the other hand, has a large time to LoS, a small heading should resolve the conflict. However,

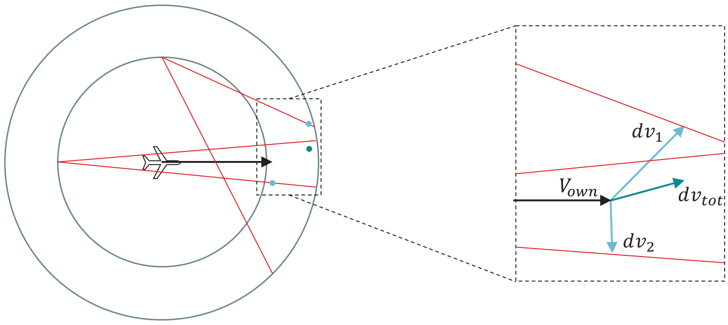
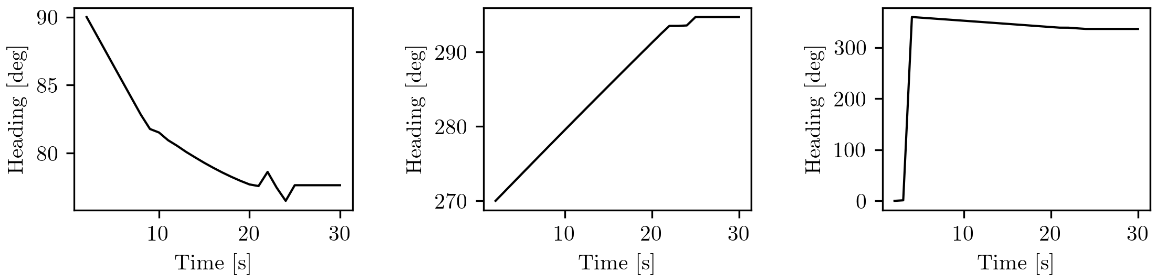


Figure 3.11: The ownship SSD of the conflict shown in fig. 3.10. The resolution suggested does not solve any conflicts as dv_{tot} is inside the velocity obstacles of both intruders. This conflict is undersolved by the ownship.

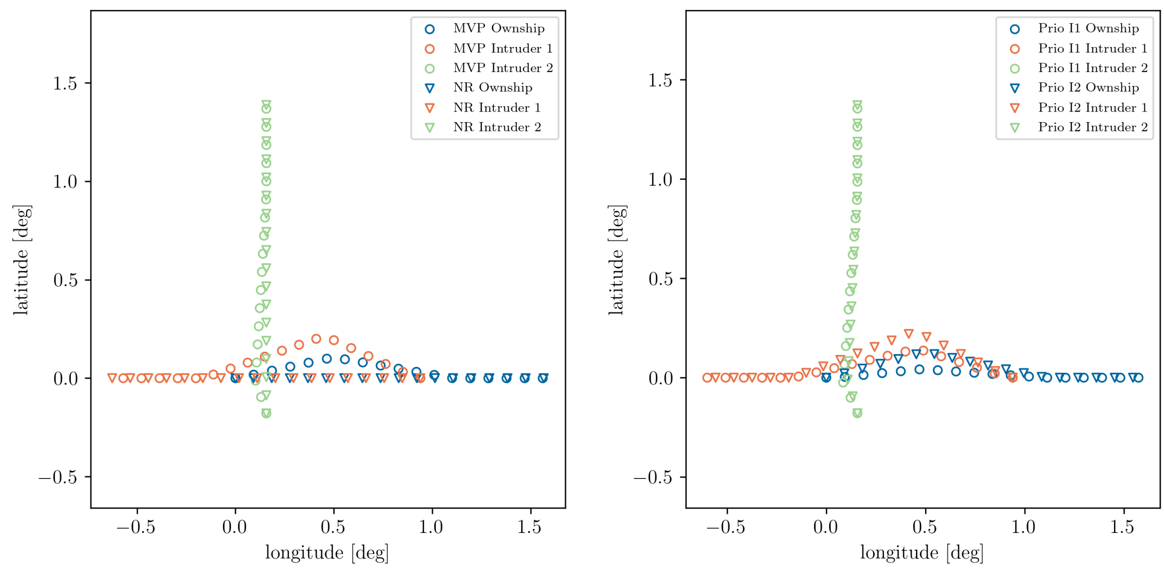


(a) Ownship heading over time (b) Intruder 1 heading over time two. (c) Intruder 2 heading over time

Figure 3.12: Heading over time of the aircraft involved in conflict fig. 3.10. The heading change of intruder 1 and 2 is constant during conflict resolution as they are maneuvering at the limit. The ownship heading change shows a full resolution of the conflict with intruder 2 at the start, followed by a more moderate heading change when the dv of both conflicts is more similar. The zigzag at the end shows sequential resolution of intruder 2 and 1.

the ownship counteracts the resolution activities by intruder 1, due to the effect of intruder 2. This causes large heading changes before conflict 2 is solved and the ownship starts cooperating in solving conflict 1. Additionally, both aircraft will only revert back to their path after t_{cpa}, which explains the large path deviation. A weighting could reduce the deviation of the ownship and intruder 2 by prioritizing conflict 2 at an earlier stage, although it should not go at the cost of a LoS with intruder 1. This potential is clearly seen when fully prioritizing the conflict with intruder 1 or intruder 2, as shown in fig. 3.13b, here one of the conflicts is completely prioritized when the ownship is simultaneously in conflict with both intruders. The behaviour shown in this figure becomes more clear when looking at the heading changes over time as shown in fig. 3.14.

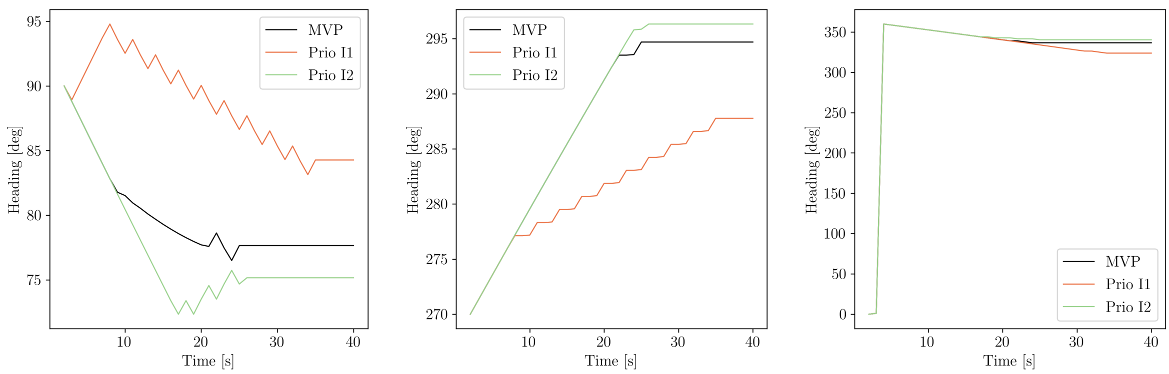
During the first part of the conflict resolution, a steady heading change in one direction is seen, in this phase the ownship is in conflict with both aircraft at the same time and completely prioritizes one of the conflicts, i.e. one conflict has weight one and the other has weight zero. After the first phase, a zigzag starts during which the ownship is alternately in conflict with one aircraft and with both aircraft. Heading changes in an effort to solve the single conflict push the ownship back into conflict with both aircraft, but does not solve that conflict before getting. At that point, the same aircraft as before gets priority. This cycle repeats itself until the aircraft are expanded enough to all stay conflict free. It is clear that the prioritized conflict is solved more efficient, which goes at a cost of the efficiency of the other conflict. The prioritized is solved largely cooperative, where the intruder has a more significant part in solving the other conflict when compared to the ownship. That is because the intruder continues solving the conflict, when the ownship is changing heading. It should be noted that prioritizing a conflict might decrease the final heading and therefore the path deviation, but that the zigzagging movement can potentially lead to an increased number of conflicts, as the extra distance searched by the CD module increases.



(a) Significant path deviation for all aircraft as a result of conflict resolution, compared to the original path.

(b) Prioritizing the conflict with intruder 1 $I1$ results in smaller path deviation for the ownship and intruder 1, compared to prioritizing the conflict with intruder 2 $I2$

Figure 3.13: Aircraft path using various conflict resolution to solve conflict fig. 3.10.



(a) Ownship heading over time

(b) Intruder 1 heading over time two.

(c) Intruder 2 heading over time

Figure 3.14: Heading over time of the aircraft involved in conflict fig. 3.10, when solving the conflict using the unweighted MVP algorithm, fully prioritizing the conflict with aircraft 1 and fully prioritizing the conflict with aircraft 2. Fully prioritizing one conflict results in a longer conflict duration and more frequent heading changes, but decreases path deviation when prioritizing conflict 1.

Conflict situation 3

Now consider the example in fig. 3.15 and its SSD in fig. 3.16. In this example, dv_1 and dv_2 almost have the same absolute value and are exactly opposite. Therefore, the sum is near zero and MVP algorithm does not find a direct solution, so the conflicts are under solved. Like in the previous example, a solution can be found after iterations of the unweighted MVP algorithm or by sequentially resolving the conflicts. However, there is no benefit of sequential resolution in this situation. Due to the geometry of this example, the avoidance vector needed for both conflicts is nearly the same. Therefore, the benefit of cooperating in solving one conflict will go at an equal cost for the other intruder, so the net profit for both intruders is near zero, while the ownship has made a deviation. When the ownship would not make a deviation, the summed deviation of the intruders would not decrease. Therefore the deviation of the ownship and the intruders combined increases. This can be seen best in the heading fig. 3.17 changes over time. The path for conflict resolution is shown in fig. 3.18.

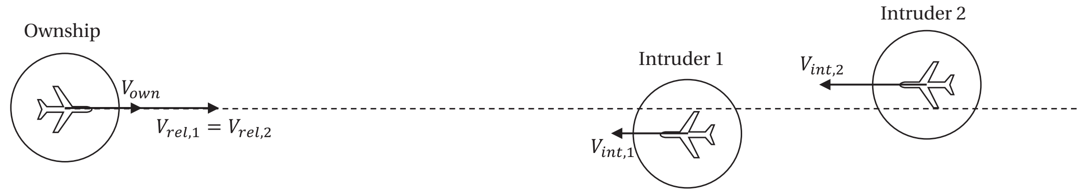


Figure 3.15: Conflict geometry which leads to undersolving of the ownship

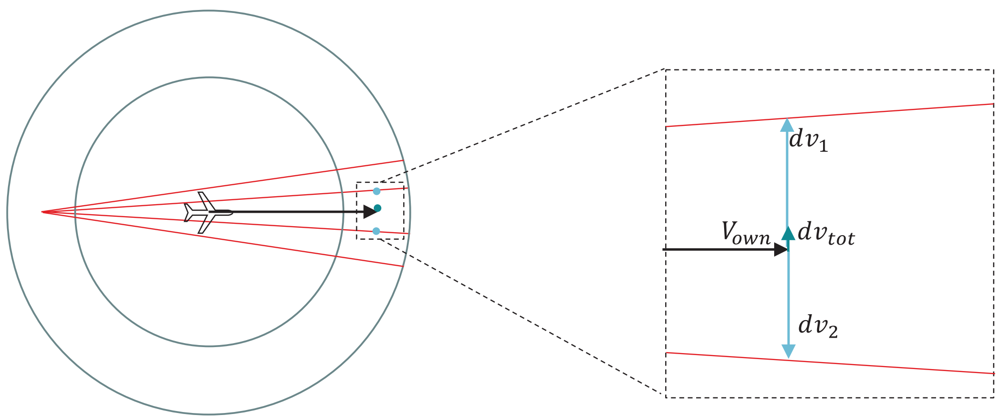
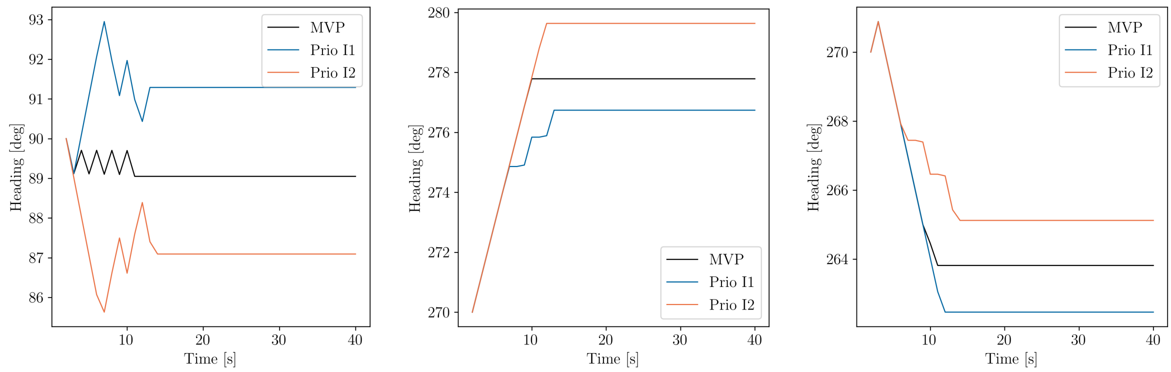


Figure 3.16: The ownship SSD of the conflict shown in fig. 3.15. Both dv have almost the same size and are in opposite direction, therefore dv_{tot} is near zero. Iterations are needed to solve the conflict, without iterations the conflict would be undersolved.

3.5. Conclusion

In this chapter the conflict resolution mechanics are analysed. It is found that the iterative solving plays an important role in solving conflicts, as it decreases the unnecessary large path deviations in case of undersolving. It also plays an important role in case of undersolved conflicts, as it creates the possibility for solutions which are not found on the SSD. Opportunities of improvement are identified in further reducing overshooting in case all avoidance vectors suggest a maneuver to the same side. Additionally, it is found that in some cases of undersolving it is beneficial to prioritize one conflict over the other.

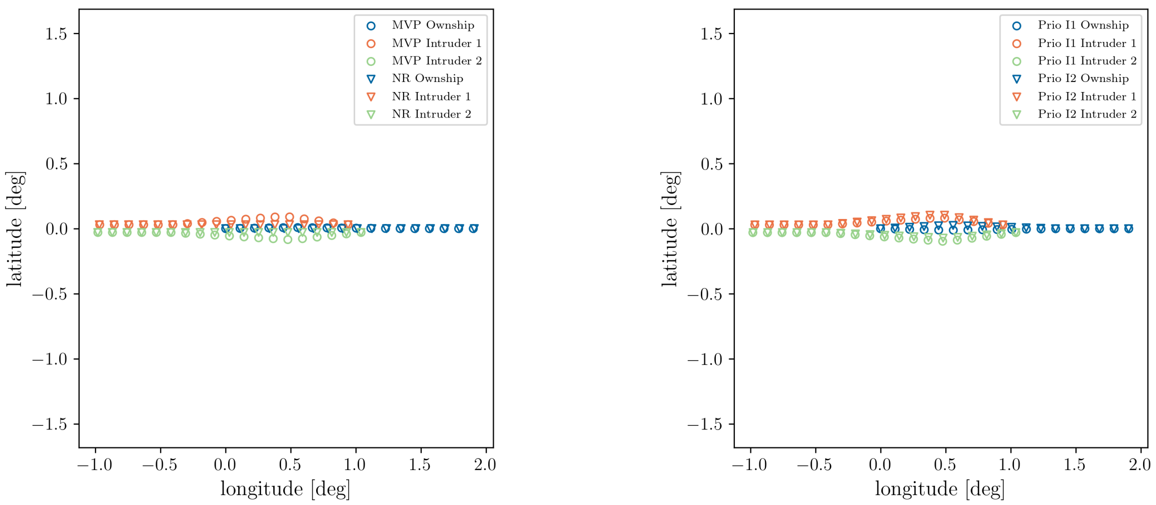


(a) Ownship heading over time

(b) Intruder 1 heading over time

(c) Intruder 2 heading over time

Figure 3.17: Heading over time of the aircraft involved in conflict fig. 3.16. Conflict resolution of the ownship is at a cost of the other conflicts resolution



(a) Small path deviation for all aircraft when solving fig. 3.15.

(b) Prioritizing one conflict over the other further slightly increases path deviation when solving fig. 3.15, compared to the unweighted MVP method.

Figure 3.18: Aircraft path using various conflict resolution to solve conflict fig. 3.15.

4

Weighted Algorithms

This section will elaborate on the development of weights to improve conflict resolution in terms of safety, stability, or efficiency by decreasing heading changes or prioritizing more urgent conflicts. Additionally, the weightings developed and tested at this point are intended to give an indication of the potential impact of a weighted solution. Therefore, a variety of weightings are developed, of which some are working on a quite opposing philosophy. The weights discussed in this chapter will be further tested in large scale experiments, where the airspace is simulated in free flight, as will be discussed in chapter 5 and chapter 6.

4.1. Averaged

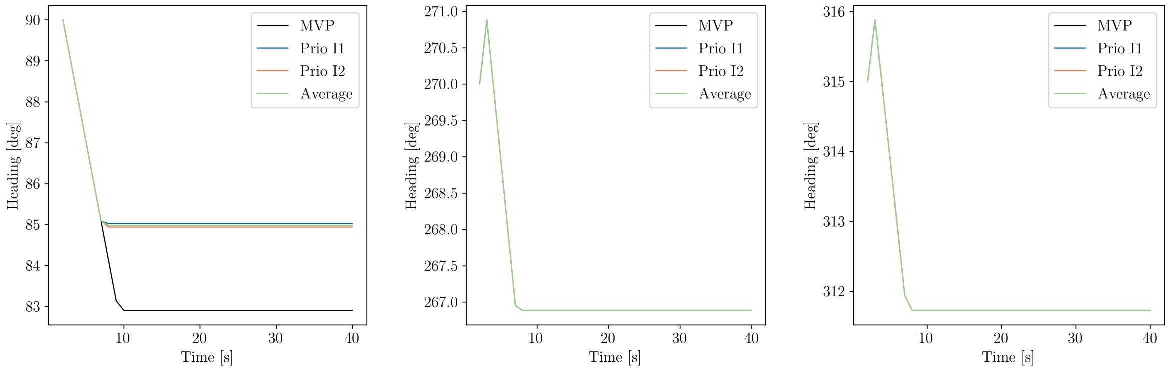
In section 3.4.1 it is shown that a conflict with all resolution vectors suggesting a maneuver to the same side will result in oversolving the conflict by the ownship. It was also shown that fully prioritizing one of the conflicts would decrease oversolving. This is an effective way, but choosing the right conflict to prioritize might be challenging when not all solution vectors suggest a maneuver to the same side. Another way to decrease oversolving is by taking the average of all avoidance vectors instead of the sum. The average absolute avoidance vectors will always be equal to or smaller than the largest absolute avoidance vector, so overshooting can only happen in the rare case where the orientation of the average avoidance vector is a more direct way out of the velocity obstacle. The weighting is be described as shown in eq. (4.1), where n_{int} is the number of intruders in a MACC. In this case, the weighting is equal for each intruder.

$$w = \frac{1}{n_{int}} \tag{4.1}$$

This weight does not change the orientation of the dv, therefore the conflicts are solved in the same direction while both the average and the sum are outside the maneuvering and velocity limits. At some point during the conflict, the average can be inside the limits, whereas the sum is outside. Both in cases of oversolving and undersolving, this can extend the conflict duration as more iterations can be needed to find a conflict free path.

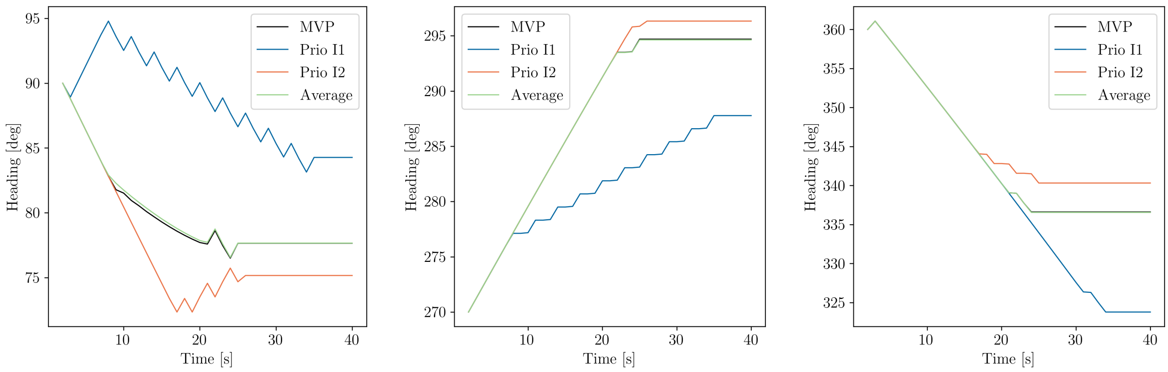
In fig. 4.1, fig. 4.2 and fig. 4.3 the heading changes of the aircraft for solving the conflicts in fig. 3.5 and fig. 3.10 and fig. 3.15 are shown. It is clearly seen that the average significantly decreases overshooting. A small deviation between the summed and averaged MVP is seen in the heading of the ownship for solving the other conflicts. In those situations, it does not lead to extra iterations needed. It even ensures a slightly smoother trajectory, decreasing the chances of extra conflicts

To conclude, the average will significantly decrease deviation compared to the sum in case of overshooting. Additionally it will ensure smoother heading changes over time. This might, however be at the cost of increased conflict time



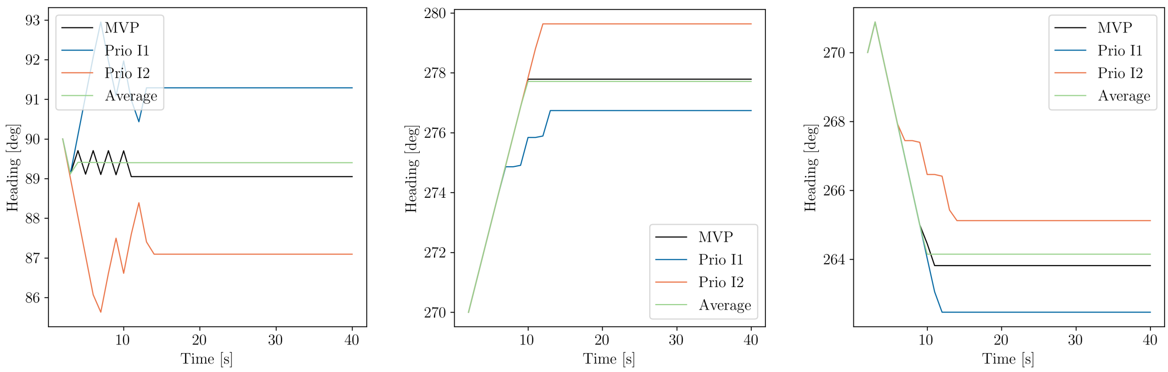
(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.1: The average of all dv reduces overshooting in solving conflict as shown in fig. 3.5.



(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.2: The average yields a similar solution as the sum of all dv when solving conflict as shown in fig. 3.10.



(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.3: The average yields a similar and slightly smoother solution as the sum of all dv when solving conflict as shown in fig. 3.15. The average finds a

4.2. Weighting on Distance or Time

Consider the case where the ownship and the intruder are in conflict and fly towards each other, like the ownship and intruder 1 in fig. 3.5. Solving the conflict at a larger distance requires a smaller heading change. Additionally, a smaller heading change requires less iterations to complete. Therefore, it is beneficial to solve this conflict at a larger distance and at larger t_{LOS}.

Now, consider the case where the ownship conflicts with intruder 1 and intruder 2, like the conflicts in fig. 3.3 and fig. 3.15. In section 3.4.2 it is discussed that it might be beneficial to prioritize conflict 2 over conflict 1 in fig. 3.10 in terms of efficiency. While solving fig. 3.15 is solved more efficient when solving both intruders at the same time.

In this section, efforts are made to develop weights based on distance or time, which will decrease the large deviations in conflicts like the first example, without compromising the efficiency conflicts like the second example. As prioritizing the resolution of conflicts can go at the cost of solving the other conflict, this section will also look at the opposite approach where a less efficient solution may be found but the more urgent conflict will be prioritized.

4.2.1. Largest distance weighting

In the analysis of the conflict as sketched in fig. 3.10, it is shown that the large heading deviation of the ownship and intruder 1 could be reduced by prioritizing conflict 1. Generally, when an aircraft is further away, the conflict can be solved faster as a smaller heading change is needed for the same intrusion. This analogy is used to compose the weight in this subsection.

A weight for conflict i (w_i), based on the distance between the ownship and intruder i of that conflict ($d_{O,I}$) and the average distance between the ownship and the intruders of that MACC ($d_{average}$) is suggested in eq. (4.2). This weighting will give conflicts where the distance between the ownship and the intruder is smaller than the average distance a weight below one, conflicts where the distance between the onwship and the intruder is larger than the average distance will have a weight above one. It will mainly impact cases where the dv are acting in opposite directions, as it may change the direction in which the ownship starts solving the conflicts. When the difference in distance is smaller, as in the conflict in fig. 3.15, the weights will be closer to one. The weight will be referred to as the largest distance priority weighting. The name might be slightly misleading as the conflict with the largest d_i will have a higher weight, but it will not be fully prioritized, i.e., other conflicts will have a weight above zero.

$$w_i = \frac{d_{O,I}}{d_{average}} \tag{4.2}$$

In fig. 4.4, fig. 4.5 and fig. 4.6 the impact of the largest distance priority, referred to as Distance LP, weighting on the heading changes of the aircraft involved in the conflict situations of the previous chapter is shown. This weighting does not have a clear effect on oversolving, as the first situation shows. The sum of the weights will be larger than one, therefore the solution will still be found far outside the SSD rather than at the border and oversolving will occur. The weights do have a clear effect on the situations where oversolving occurs, so on the second and third situation. In the second situation, the ownship starts maneuvering in the opposite direction as it does with the unweighted MVP algorithm, similar to Prio I1. It does, however, not fully solve that conflict, but starts solving the other conflict halfway through. Eventually, this does not lead to a decreased deviation for the ownship, but it does for intruder 1 at a cost of the deviation of intruder 2 and a slightly less smooth resolution for all aircraft. Thus, it could be seen as a more moderate version of the full prioritization. Therefore, still providing an opportunity for decreased deviation for some aircraft involved, but at a lower risk of LoS. The effect of the weights on the last situation is a bit smaller, no clear difference in the final heading change is seen, but the weight does ensure a smoother resolution of the ownship compared to the resolution with the MVP algorithm.

It should be noted that prioritizing the conflict farthest away comes with a risk of getting in a LoS with the aircraft closest by, as this conflict may not be solved, this risk is partly counteracted by two elements. First, conflicts closer will have a larger dv compared to conflicts further away with the same intrusion, because the t_{LOS} is smaller. A larger dv might compensate for a smaller weight, therefore the conflict can still be solved.

Second, this weighting only applies to situations when multiple aircraft are in conflict at the same time. Since, the lookahead time used in this research is 300 seconds and conflicts are both solved when it has the largest weighted dv or when it is not part of a MACC, the chances are small that a conflict does not have enough time to be solved. Both arguments hold in most cases, although they lose strength when looking at shallow angle conflicts. The angle between aircraft velocity vectors in shallow angle conflicts is small, therefore the relative velocity is small and the distance between aircraft might be small at the start of the conflict. Additionally, it was observed by Sunil [18] and Balasooriyan [1], that solving those conflicts by the MVP algorithm can take a long time. When the ownship is part of shallow angle conflict with intruder 1 and gets in conflict with intruder 2, it is part of a MACC. The counteracting $w_2 \cdot dv_2$ might cause the ownship to maneuver into the protected zone of intruder 1.

At this point, it is clear that the weighting method comes with the risk of decreased safety in particular cases. A decreasing the risk would not be acceptable in free flight where self-separation needs to be assured. The possibility of increased number of LoS in larger simulations is however low. On the other hand, this method has the benefits of decreased deviation and heading changes. A better gasp of the advantages and disadvantages should appear from the large simulations.

4.2.2. Smallest distance weighting

Opposite to the weighting based on the largest distance, it is also possible to weight based on the smallest distance using the inverse of eq. (4.2) as shown in eq. (4.3). This algorithm has quite opposite characteristics compared to the one before. Conflicts close by will get a higher weighting, reducing the chances of LoS, although this goes at a cost of efficiency and stability. Aircraft will on average get closer before the conflict is solved, therefore larger deviations are needed to solve the conflicts. Additionally, this leads to increased conflict time. This weighting will be called the smallest distance priority weight (Distance SP).
The effect of this smallest distance priority weight on the heading of the aircraft in the examples used before is shown in fig. 4.4, fig. 4.5 and fig. 4.6. The weight also does not effect oversolving. In the second and third example, a somewhat opposite effect is seen compared to the largest distance weighting. The heading change of the ownship is in the opposite direction at the conflict start. In conflict situation two, the heading change of intruder 2 is smaller. Due to the full cooperation of the ownship, a conflict free path is found sooner. This is, however, at the cost of the conflict duration of conflict 2, as well as an increased heading change of the ownship and intruder 1. Thus, the more urgent conflict is solved faster at a cost of extra deviation of the aircraft involved in other conflicts. In the last example, the final headings are again similar. Although the conflicts are solved less smooth. The smallest distance weighting increases the difference between the weighted **dv**, where the largest distance weighting decreases the difference. The large difference induces the sequential resolution seen in the zigzagging of the heading.

$$w_i = \frac{d_{average}}{d_{O,I}} \tag{4.3}$$

It is expected that the results of weighting on the smallest distance and weighting on the largest distance will show somewhat of a stretch of possible improvements by adding weights to the MVP algorithm. The smallest distance is expected to decrease the number of LoS in large simulations, at the cost of stability and distance flown. Opposite to the largest distance weighting method.

4.2.3. Largest time to LoS weighting

Similar to the weighting based on the largest distance, a weighting based on the largest t_{LOS} can be composed, as shown in eq. (4.4). Here t_{LoS_i} is the time to LoS between the ownship and intruder i, $t_{LoS_{average}}$ is the average time to LoS between the ownship and all intruders part of the MACC. This weighting method will be referred to as largest time to LoS priority, or simple largest time priority.

$$w_i = \frac{t_{LoS_i}}{t_{LoS_{average}}} \tag{4.4}$$

The weights of time and distance will indeed be the same for head-on collisions where all relative velocities are the same, the difference will occur for other angles, so when the relative velocities are not the same. This is most clearly seen in shallow angle conflicts, here the distance between the ownship and the intruder can be small, while the time to LoS is large. As explained in section 4.2.1, the largest distance weight does not perform well for shallow angle conflicts, so in those situations the largest time weight might perform better. The largest time weighting is on the other hand, naturally more sensitive to under prioritizing conflicts with smaller t_{LOS} and therefore the possibilities of LoS are higher.

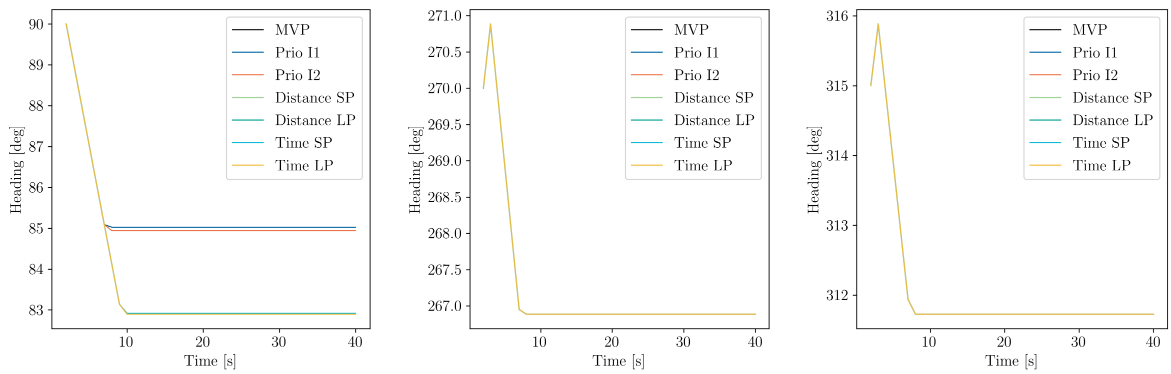
The effect of the largest time priority method on the conflict situations discussed before is also shown in figures fig. 4.4, fig. 4.5 and fig. 4.6. The effects of this methods are similar to the largest distance priority weighting, as the conflict angles are large, so $t_{LOS,i}$ is large where d_i is large and small, where d_i is small. Therefore, the results in the airspace simulations are expected to be similar as well. The differences will be driven by the variation in conflict angles. It is expected that the conflict time and deviation of the largest time method is on average slightly lower as the negative effects of shallow angle conflicts will be lower. On the other hand, the number of LoS might be slightly higher for the number the largest time weighting as more urgent conflicts are further underprioritized.

4.2.4. Smallest time to LoS weighting

As was done with the largest distance weight, the largest time weight can be inverted as well, as shown in eq. (4.5). This equation provides conflicts with low t_{LOS} with a high weight, so it prioritizes more urgent conflicts to prevent LoS at the cost of efficiency, stability, and conflict duration. The differences between the smallest time to LoS priority and the smallest distance priority are also driven by the conflict angles. Since the conflict angles are large in the conflict situations discussed, the results are also similar, as shown in fig. 4.4, fig. 4.5 and fig. 4.6.

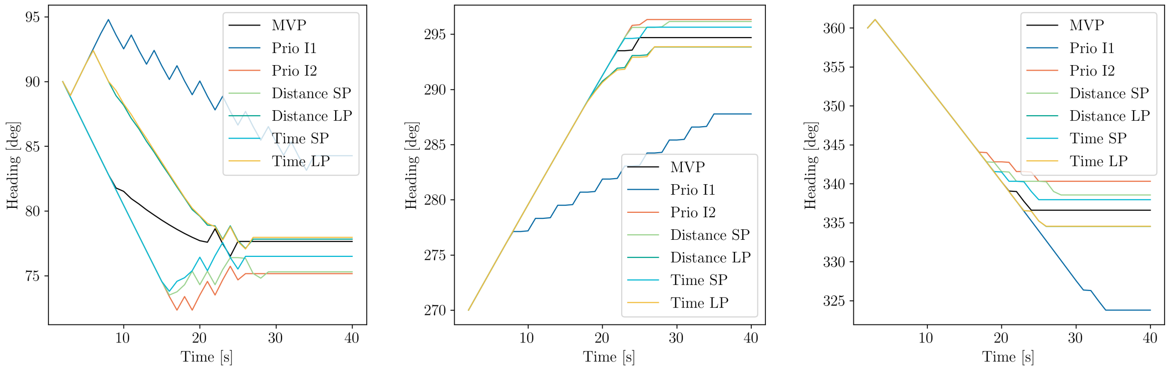
$$w_i = \frac{t_{LoS_{average}}}{t_{LoS_i}} \tag{4.5}$$

In the large simulations this method is expected to behave similar to the smallest distance weight. Differences will also here be driven by conflict angles. Smaller conflict angles can result in high t_{LOS} while the distance is small. In those cases the small distance weighting will prioritize while the small time method does not. Therefore, conflict time in those situation might further increase for the smallest time weighting.



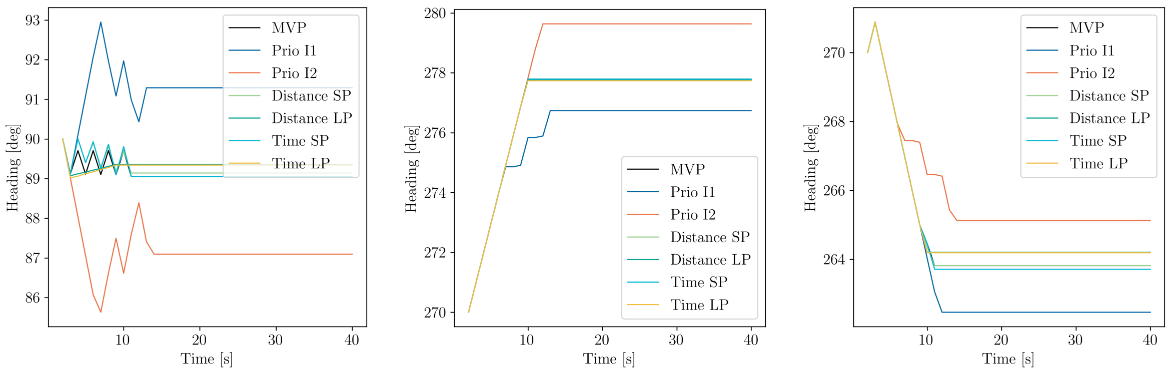
(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.4: Time and distance weights do not have effect on the heading over time of aircraft involved in conflict fig. 3.5.



(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.5: Time and distance weights effect the heading over time of aircraft involved in conflict fig. 3.10. The largest distance and time weights show almost identical conflict resolution, resulting in a final heading of the ownship comparable to the unweighted MVP. This is however reached differently, leading to a reduced heading change of intruder 1 and a decreased heading changes of intruder 2. Prioritizing smallest distance and time increases heading change of the ownship and intruder 1, while it decreases heading change of intruder 2.



(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.6: Time and distance weights slightly effect the heading over time of aircraft involved in conflict fig. 3.15. The final difference in final heading changes are small, as is the heading over time for weights on prioritising smallest distance and time. The weights prioritising largest distance and time follow more smoothly converge to the final heading.

4.3. Weight Based on dv

The previously discussed weights result in moderate changes in conflict resolution compared to the unweighted MVP. Changes could become larger when fully prioritizing one conflict or one maneuvering direction, as discussed in section 3.4. One way to fully prioritize one conflict over the other is by weighting a conflict with zero or one based on the size and direction of the suggested avoidance vectors, two variations of this method will be discussed in the remainder of this section.

4.3.1. Smallest dv weighting

The conflict resolution path can be changed in an effort to decrease the deviation by weighting based on the size of the individual dv. fig. 3.12 shows that the ownship strongly changes heading during the iterative solving of the represented conflict situation, especially when one of both conflicts is fully prioritized a zigzag profile is seen. In section 3.4.2 it was explained that the ownship does not cooperate in both conflicts equally. It first fully resolves the prioritized conflict in full cooperation with the intruder. Then it starts resolving the other conflict but does not fully share the resolution, here the intruder is responsible for the largest part of the resolution. This causes the ownship to first move from its original heading and then moves back to it. The order in which the conflicts are solved, is of influence to the heading deviation at the end of the conflict. The predicted intrusion in both conflicts at the start of the conflicts needs to be resolved, this translates to a **dv** per conflict which needs to be completed cooperatively by both aircraft. Thus, when first fully solving the smallest absolute **dv** and then partly solving the largest absolute **dv** will result in a smaller final heading deviation for the ownship. For the prioritized intruder this results in a smaller deviation as well, although for the other intruder this results in a larger deviation. When looking at the sum, this may be a more efficient solution.

The suggested algorithm fully prioritizes the smallest dv, so it is assigned a weighting $w = 1$, the other dv is assigned a weighting $w = 0$. In case of more than two intruders, the sum of absolute dv per side is taken and all dv on the side of the largest sum get weight $w = 1$, the others are assigned $w = 0$.

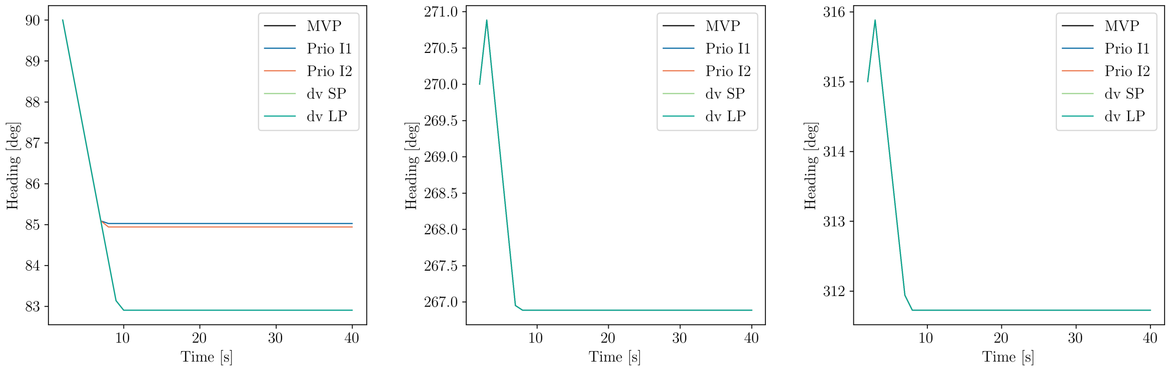
The effect of this method on conflict resolution is shown in fig. 4.7, fig. 5.2 and fig. 4.9. The resolution consistently coincides with Prio I1 or Prio I2, as expected. Thus, the benefits of this algorithm are found in decreased deviation. The risk that assigning priority to the smallest dv leads to a LoS is even larger than in cases of weights based on the largest distance or time to LoS as now the weight assigned is zero. Although it should be kept in mind that the possibility that a conflict during the full conflict duration has continuously a smaller dv is low. Additional downsides of having binary weights are the zigzag movement in the heading, which causes a larger area scanned for conflicts and might lead to more conflicts and decreased stability. It should be noted that with a higher time step, the zigzagging would be reduced.

4.3.2. Largest dv weighting

As with the the distance and time to LoS weight, this weight can be inversed as well. By assigning the weight $w = 1$ to the largest dv and $w = 0$ to the smallest dv. In general, a more urgent conflict is now prioritized, increasing safety at the cost of efficiency and stability.

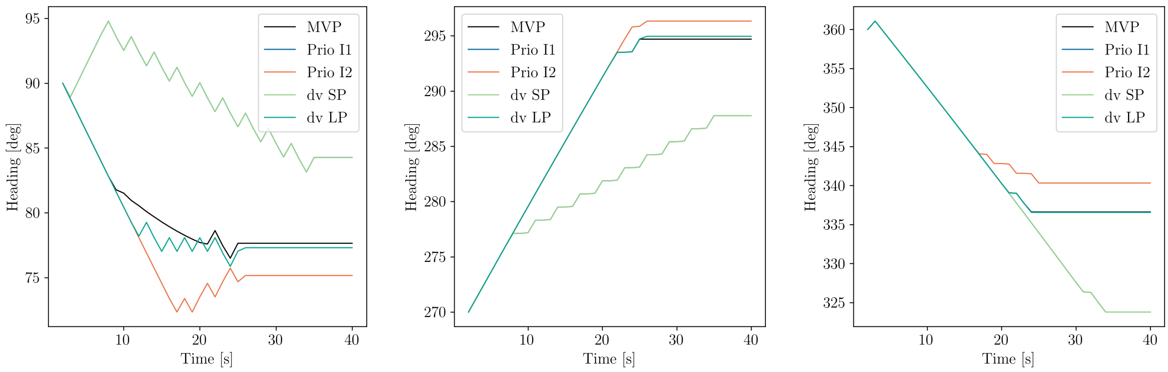
The effect of this method on conflict resolution is also shown in fig. 4.7, fig. 5.2 and fig. 4.9. Contrary to the smallest dv weighting method, this method does not constantly coincide with Prio I1 or Prio I2. By prioritizing solving the conflict with the largest absolute dv, the size of dv decreases as the intrusion decreases. At some point it becomes smaller than the other dv, at that point the solution starts to differ from the full prioritizing of one aircraft. This is clearly seen in the second and third conflict situation. The final headings of all aircraft are close to the situation where conflicts are solved using the MVP algorithm. Although the solution is less smooth as more heading changes are present, this will result in a destabilizing effect on the airspace.

It is expected that this method will result in a lower number of LoS at the cost of larger deviation when compared to the smallest dv weighting. The destabilizing effect is expected to be similar.



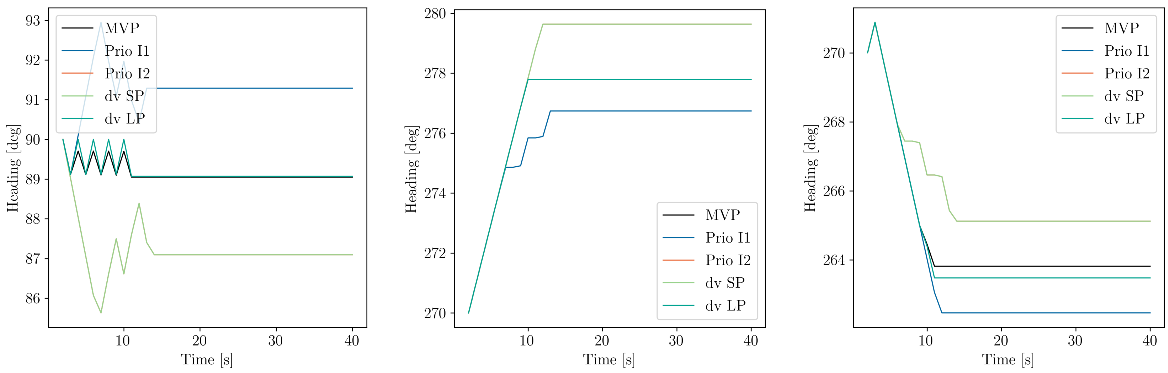
(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.7: Smallest priority *SP* and largest priority *LP* dv weights do not have effect on the heading over time of aircraft involved in conflict fig. 3.5.



(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.8: Weighting based on dv effects the heading over time of aircraft involved in conflict fig. 3.10. The smallest priority *LP* weight follows the path of the prioritized conflict with the smallest dv, conflict 1 in this case. The largest priority *LP* finds it solution closer to the unweighted MVP, it deviates from the Prio I2 when dv_2 becomes smaller than dv_1 due to the resolution activities. Similar to Prio I1 and Prio I2 Strong zigzag motion is seen.



(a) Ownship heading over time (b) Intruder 1 heading over time (c) Intruder 2 heading over time

Figure 4.9: Weighting based on dv effects the heading over time of aircraft involved in conflict fig. 3.15. The smallest priority *LP* weight follows the path of the prioritized conflict with the smallest dv, conflict 2 in this case. The largest priority *LP* finds it solution closer to the unweighted MVP, it deviates from the Prio I2 when dv_2 becomes smaller than dv_1 due to the resolution activities. Similar to Prio I1 and Prio I2 Strong zigzag motion is seen.

4.4. Conclusion

Summarizing, seven weighting methods have been composed in this chapter. The methods are developed with different goals in mind and should therefore show a variation in results when simulating in a a larger simulation. The average weighting will decrease overshooting and cause a smoother resolution trajectory, at a cost of conflict time. The largest time and distance weights are developed to decrease deviation undersolved conflicts, this will be at a potential cost of increased number of LoS. The largest time weight is slightly more sensitive to underprioritizing more urgent conflicts, while it might better deal with shallow angle conflicts. The smallest distance and time method show somewhat opposite characteristics as they decrease chance of LoS at a cost of increased deviation. The difference is also here found in the shallow angles, where t_{LoS} is high while the distance is low. Those conflict will have a higher duration when part of a MACC when resolved with the smaller time weight. The smallest and largest avoidance vector prioritisation show more extreme behavior, as maneuvering to one side is fully prioritized. The largest absolute **dv** priority tries to prioritize more urgent conflicts, where the smallest absolute **dv** priority is focused on decreasing deviation. Both show large zigzag maneuvers in the heading change, which might lead to decreased airspace stability.

The variety in objectives should provide a gasp of the possibilities of weights and might stimulate further development of an all-round weight when there seem to be good possibilities. On the other hand there is a possibility that the effect of the weights are small. In that case it should be analysed why the differences are small and the potential effects of weights should be reevaluated.

5
Airspace simulation

The effects of multi-aircraft conflict resolution on the airspace in free flight can be well analysed by simulating a part of the airspace. These experiments give the opportunity to investigate the effects of multi-aircraft conflict resolution on a system level in general and the effect of the methods developed in chapter 4 specifically. Additionally, it gives the opportunity to analyze the effect of the developed methods on a variety of MACC.

The remainder of this chapter will first elaborate on the simulation in section 5.1. Then the development of the airspace simulation is explained. in section 5.2. Finally, the experiment parameters and variables will be discussed in section 5.3 and section 5.4.

5.1. Simulation Environment

The developed algorithms will be tested and compared to the unweighted MVP algorithm in fast-time simulations. For those simulations, the open source air traffic simulator Bluesky Hoekstra et al. [9] will be used. Bluesky is written in Python code. Bluesky is particularly suited for this research as it models the aircraft dynamics well, using aircraft characteristics, dynamic and kinetic performance details from the OpenAP library, Sun et al. [17]. The dynamic modeling ensures a well representation of real aircraft maneuvering in a conflict resolution situation, it should however be noted that the simulations do not account for human behavior. Additional benefits of using Bluesky as air traffic simulator are found in the use of Bluesky in previous conflict resolution research by Balasooriyan [1], Sunil et al. [20] and Ribeiro et al. [15]. Frequent use in previous work can be seen as a form of validation and the results gained in this research can be compared with results from other research. In Bluesky conflict detection and conflict resolution among which the MVP algorithm are already programmed and tested, therefore it is ready to be used in this research as well and the results can be compared.

5.2. Airspace Traffic Scenario Development

In the simulation, aircraft origin and heading are uniformly distributed and fly in a straight line to represent the airspace in free flight. Aircraft are simulated within the simulation area, which is defined as a large square, when an aircraft crosses the border of the simulation area, it will be deleted. Within the simulation area, the experiment area is defined. The size of both squares is defined in section 5.3. While aircraft are simulated in the simulation area, only the data generated by aircraft in the experiment area is used in the experiments. Aircraft will find their origin in the strip between the borders of the simulation area and the experiment area at a distance two-and-a-half times the average look-ahead distance, where the look-ahead distance is the look-ahead time multiplied by the average ground speed, from the experiment area border, so that aircraft in the experiment area will not suddenly get in conflict with the spawning aircraft. The aircraft destinations are near the experiment border, at an altitude just below the simulation floor. Aircraft will therefore cross the simulation floor just before the destination and be deleted at that point. The simulation of part of the airspace is modified from the simulations used by Sunil et al. [20] and [13]. The main difference is the spawn location and destination, as those were placed at the edges of the inner area. Therefore there is a larger probability of aircraft being in a short term conflict just after they spawned, in the methods used by Sunil et al. [20] and [13].

When an aircraft is in conflict, it might deviate from its route and therefore not directly fly over a waypoint. In those cases where an aircraft misses a waypoint, the waypoint will be deleted from the itinerary and the aircraft will fly to the next waypoint in line where possible, therefore waypoints are regurly placed over the planned route. When a waypoint is missed, the designated altitude at the missed waypoint will not be adhered to, instead the aircraft will continue flying at its current altitude. When there are no more waypoints after the missed waypoint, the aircraft will revert back to the missed waypoint after conflict resolution, to do so the aircraft might need to perform a u-turn like move. Thus, if the destination is missed, the aircraft needs to make a large maneuver at the area where aircraft are spawned, this might lead to conflicts with aircraft which are just spawned and result in them leaving their route before participating in the experiment. This unwanted behaviour is decreased when aircraft revert to the route instead of to the missed waypoint as a smaller maneuver is needed. Therefore, a backup destination is set just outside the simulation area. The backup destination ensures that aircraft continue their flight with a heading similar to their original heading until they leave the simulation, after the intended destination was missed due to conflict resolution. Although, in reality aircraft would not have a backup destination, it is useful to have it in the simulations to decrease disturbance in the measurements. An example of a planned route is shown in fig. 5.1

The scenarios are off-line created with a Python script and uploaded to Bluesky before simulating. Those scenarios contain the spawn time and route per aircraft. The script calculates the route of all aircraft separately as described below. The airspace density is ensured as described in section 5.2.1. The paths of aircraft are generated in four steps. First, a uniformly generated route origin is assigned to the aircraft. Second, a uniformly generated heading is assigned and it is checked if the destination is inside the experiment area, else steps one and two are repeated. Third, a spawning location is set at the defined distance from the origin. The heading from the spawning location to the route start is the same as the route heading. Fourth, a backup destinations is set outside the border of the simulation area, at the same altitude as the original destination.

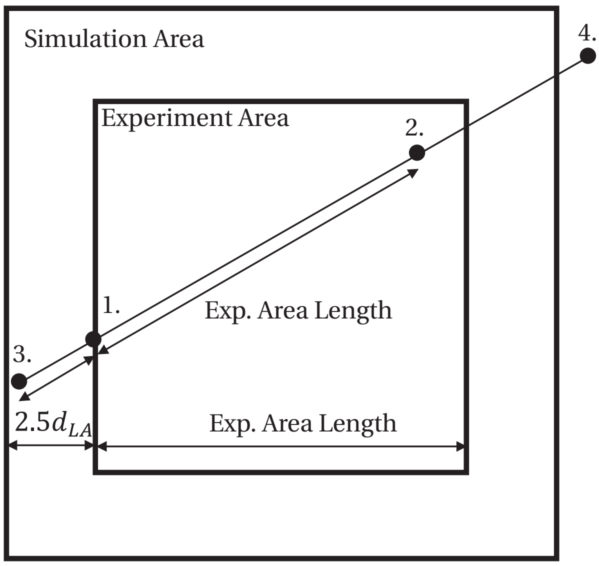


Figure 5.1: The geometry of the spawned airspace and an example of the planned route. With 1. Route origin, 2. Route destination, 3. Spawn location, 4.Backup destination.

5.2.1. Density Regulation

The density in the simulation area is controlled by spawning aircraft at the same rate as they are deleted. Thus, after an aircraft finishes its route, it will be deleted because it leaves the simulation area, at that point a new aircraft is spawned. The spawn rate Ω is calculated using eq. (5.1) Sunil et al. [19], where $\mathbf{D}$ is the average distance flown in the experiment area, $\mathbf{v}$ is the average velocity, and N is the number of instantaneous aircraft in the simulation area. It should be noted that the spawn rate is calculated based on the average distance and velocity planned. During conflict resolution, the aircraft might deviate from their path and change velocity, which will drive a slight variation in the planned route.

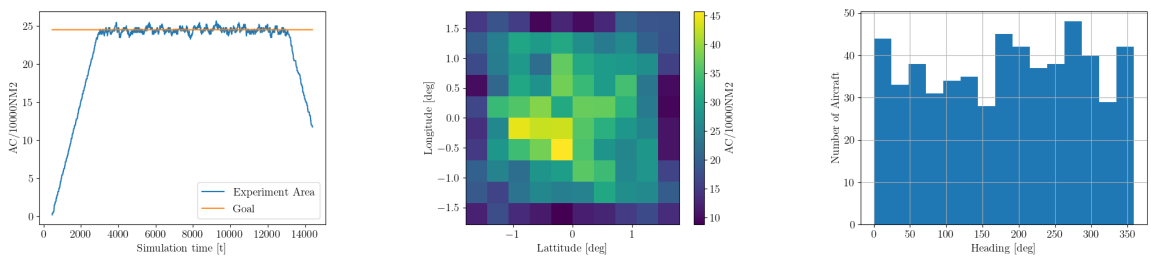
$$\Omega = \frac{\mathbf{D}}{\mathbf{v}} N \tag{5.1}$$

To ensure that the density is at the designed level when measurements start, a build-up period is needed. During this build-up period, the airspace density will increase up until the designed level.

5.2.2. Airspace Traffic Scenario Analysis

The scenario generation described, causes variation in local airspace density as aircraft may be deleted just before the border and the routes are more likely to go through the middle section than along the borders. Therefore the density near the borders will be below average and near the center will be above average. For the experiments in this research it is not necessary to have a perfectly distribute density. Simulating aircraft in a direct route from origin to destination in an unorganized airspace, with a significant possibility to get in multi-aircraft conflicts is most important. It is sufficient to be able to increase density to increase the possibilities of MACC and to analyse the behaviour in a more dense airspace compared to a less dense airspace.

The density over time and the density distribution for a simulation with a set density of 24.5 $AC/10000Nm^2$ are shown in fig. 5.2a and fig. 5.2b, respectively. The corresponding heading distribution of the aircraft in this simulation is shown in fig. 5.2c. It is shown that indeed an build-up period is needed and that after the build-up period the density is about constant for the duration of the experiment. The average density is lower near the borders and gets higher towards the center. The aircraft heading is not completely uniformly distributed, as the number of aircraft is relatively low per bin, there will be naturally an offset when the heading is generated using a random sampling algorithm for a uniform distribution.



(a) The density is quite constant and at the expected level for the duration of the experiment. An steady density increase is seen during the 3000 second build-up period. After the experiment ends the density decreases as no more aircraft are spawned.

(b) The density distribution in the experiment area during the experiment. The density is lower at the borders and increases near the center due to the route generation logic.

(c) The heading distribution in the experiment area during the experiment. The distribution is not completely uniform as the number of aircraft per bin is relatively low and heading is generated using a random sampling algorithm for a uniform distribution

Figure 5.2: Characteristics of a scenario where aircraft do not use a CR algorithm. The density is set at 24.5 $AC/10000Nm^2$, the experiment starts after 3600 seconds and ends after 12600 seconds

5.3. Experiment Parameters and Independent Variables

In this section, an overview of the simulation parameters and independent variables used in the preliminary experiments is provided. The results of the experiments can be found in chapter 6.

The simulation parameters are shown in table 5.1. The flight level and velocity range are chosen such that there is sufficient margin to increase or decrease velocity, the minimum TAS of a B744 at FL100 is 162 kts, and its maximum TAS is 406 kts, while the instructed TAS is between 291-322 kts. The look-ahead time and ASAS time step are the same as commonly used, as discussed in section 2.2 The protected zone radius is set to 5 NM, according to regulations. The distance of the planned route is set to 214.5 NM, which corresponds to a

Table 5.1: Simulation Parameters

Parameter	Value
Δt_{ASAS} [s]	1
$t_{LA}[s]$	300
$r_{PZ}[NM]$	5
$T_{exp}[h]$	2.5
$T_{sim}[h]$	3.5
$A_{exp}[NM^2]$	46001
$Aircraft\ type$	Boeing 747-400
$d_{NR}[NM]$	214.5
$TAS[kts]$	291-322
$Flight\ Level$	FL100

flight time of 0.7 hours inside the experiment area and an experiment area of 46001 NM^2.

The independent variables in this research are the airspace density and the conflict resolution methods as discussed in chapter chapter 4 and the airspace density. Three relative high airspace densities are chosen to increase the possibility of MACC and therefore better test the effects of the developed algorithms. The densities are 20.0, 24.5, and 30.0 $AC/10000Nm^2$. The conflict resolution algorithms are listed below.

- No conflict resolution
- Unweighted MVP
- Averaged MVP
- Largest distance priority weighting MVP
- Smallest distance priority weighting MVP
- Largest time to LoS priority weighting MVP
- Smallest time to LoS priority weighting MVP
- Largest dv priority weighting MVP
- Smallest dv priority weighting MVP

5.4. Dependent Measures

The performance of an algorithm can be measured in three categories, safety, efficiency, and stability on a system level or more specifically per conflict.

5.4.1. Conflict resolution measures

The measures to analyse stand-alone multi aircraft conflicts are discussed in section 3.1. In the airspace traffic simulations, the deviation per conflict and conflict time will also be evaluated. Now, the conflict duration and the number of iterations needed to solve a conflict are measured. Although both are highly related, the conflict duration is not simply the number of times the time step. The conflict duration is the time between the first and last conflict resolution maneuver, it is not necessarily the case that during every time step a conflict resolution maneuver is made. When in conflict with multiple aircraft, it is possible that at one point the conflict with one aircraft is solved, but at the next time step the conflict resolution of the other aircraft reinitiates the solved conflict, as seen in section 3.4.2. It could also be that a new conflict reinitiates an old conflict

5.4.2. System level measures

The system level measures summarize the effect of conflict resolution measures on safety and efficiency on the complete route of all aircraft and the stability of the airspace. The stability of the airspace is measured using the DEP, as discussed in section 2.4.1.

It is of utmost importance that a conflict resolution algorithm ensures safe separation. Safety is measured using two metrics. First, the number of LoS and second the intrusion severity of the LoS. The intrusion severity (LoS_{sev}) is the fraction of the protected zone radius which is violated, it is calculated using eq. (5.2)

$$LoS_{sev} = \frac{r_{PZ} - d_{cpa}}{r_{PZ}} \tag{5.2}$$

The efficiency on a system level is measured as the rate of extra distance flown d_{ext} between the origin and destination due to conflict resolution (d_{cr}), compared to the nominal distance flown when there would not be a conflict (d_{nr}). It can be calculated using eq. (5.3).

$$d_{ext} = \frac{d_{cr}}{d_{nr}} - 1 \tag{5.3}$$

6
Discussion of Results

In this chapter, the results of the experiments as presented in chapter 5 are presented and discussed, the performance of the developed methods is evaluated.

6.1. Average System Results

Before analysing the conflict resolution in terms of efficiency, stability, or safety, first the number of conflicts and the number of MACCs is analysed.

6.1.1. Number of conflicts and airspace stability

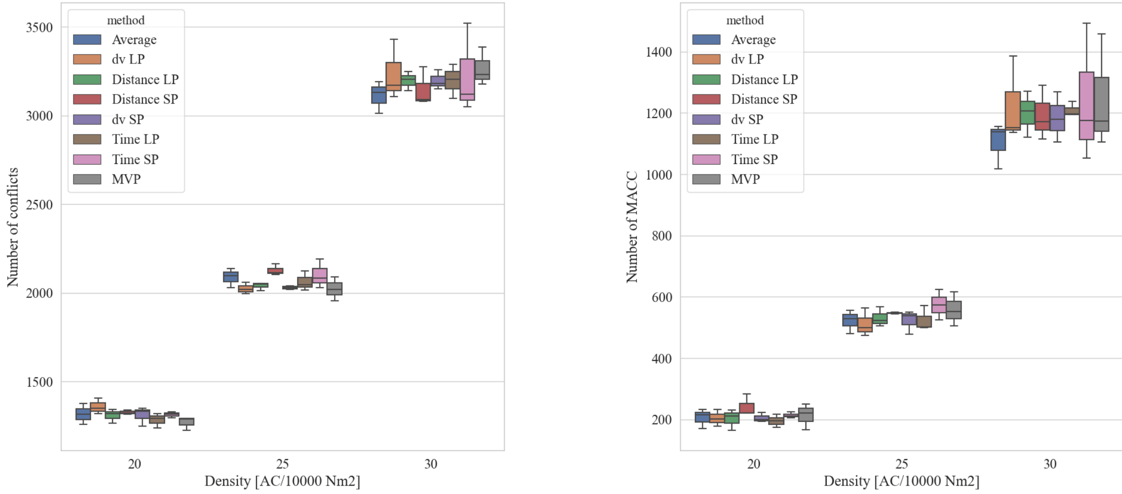
The number of conflicts and MACC are used to determine the significance of the results, if the number of MACC is low, the effects of the weight will be low as well. The number of conflicts are shown in fig. 6.1 and summarized in table 6.1. It can be seen that the number of conflicts and MACC strongly increase with an increased density, so when analysing conflict performance, the results of higher density will provide better averages. Nevertheless, the number of MACC in the lowest density is around 200, therefore the conflict resolution performance at these densities can be analysed well. Comparing the methods, little variation is seen, therefore the differences in effect on airspace stability per method cannot be clearly seen from this figure.

The DEP shown in table 6.1 are in line with the number of conflicts. It cannot be concluded whether the methods developed either increase stability or decrease stability according to the expectations. One reason could be that the effect of MACC resolution and airspace stability could be smaller than expected in general. Another reason could be that the developed weights only have a small effect on the MACC in the simulation. A third reason could be that the number of repetitions per density is too low to show a pattern on the stability performance.

In fig. 6.2, the number of timesteps at which an aircraft was part of a MACC during the full flight is shown. I.e., the number of iterations at which an aircraft was part of a MACC and the avoidance vectors were weighted. From this figure, it indeed becomes clear that the effect of weighting on most aircraft is limited to a low number of iterations. At the two lowest densities, the trajectories of all aircraft in the 75th percentile are only between one and three timesteps effected by the weights. At the highest density the 75th percentile is exposed to the weights at about a maximum six or seven steps during the complete flight. This shows that especially at lower densities, the effect of weights on a system level is limited to a small group.

6.1.2. Safety

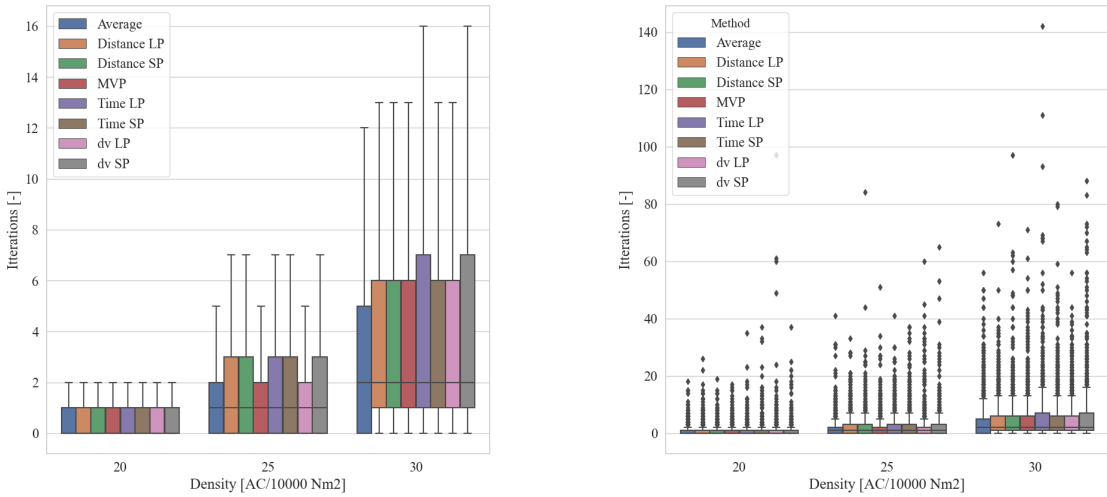
The number of LoS in table 6.1 shows small absolute differences, although not always consistent over time. Considering the low number of repetitions, one should be careful when drawing conclusions. Additionally, the intrusion severity is low for all LoS. That being sad, the fully prioritisation of the maneuver to one side as done with dv SP, seems to result in more frequent LoS, in line with the expectations. Moreover the largest dv method result seems to result in more frequent LoS, it is likely that those are caused by conflicts with small conflict angles and therefore small dv, even when the distance between the aircraft is small. It is noticed that Average and Distance LP are on the low end in those simulations. Based on this, especially the Distance LP



(a) The number of conflicts

(b) The number of MACC

Figure 6.1: The total number of conflicts and MACC in the airspace simulations.



(a) The number of MACC per aircraft per route without outliers

(b) The number of MACC per aircraft per route with outliers

Figure 6.2: The number of MACC per aircraft per route is generally low.

performs better than expected. However, once again, repetitions are low, therefore no conclusions drawn based on small differences are weak and merely and an indication of potential performance.

6.1.3. Route Efficiency

In fig. 6.3 the percentage extra distance flown per aircraft, compared to the planned route is shown. When outliers are not considered, the differences per weight are small and inconsistent over time. Therefore, there is no clear effect of the weights seen in the results. This could be caused by a small effect of MACC on the aircraft route in general. If an aircraft is only effected by a MACC for a limited number of iterations during the full flight time, the potential affect of weighting methods is low. This could be the reason due to small intrusions and therefore a low number of iterations per MACC or small changes in case of oversolving. On the

Table 6.1: The average system level results of the experiments elaborated on in section 5.2.2. The performance differences shown by the weights are small and inconsistent per density, expected to be driven by a low number of 3 repetitions and limited impact of the developed weights. The values for MVP are shown as the absolute values.

	Average number of MACC [% difference MVP]			Average number of conflict [% difference MVP]			DEP [% difference MVP]			Average number of LOS [% difference MVP]			Average LoS Severity [-]		
Density [AC/10000NM2]	**20**	**25**	**30**	**20**	**25**	**30**	**20**	**25**	**30**	**20**	**25**	**30**	**20**	**25**	**30**
MVP	222.0	588.0	1286.0	1335	2118	3393	0.33	0.38	0.50	2.7	2.7	3.7	0.00	0.00	0.00
Average	-0.2%	-6.9%	-10.8%	3.3%	3.0%	-4.4%	13.3%	11.1%	-13.2%	-75%	-50%	18%	0.00	0.00	0.00
dV LP	-3.3%	-9.1%	-0.7%	6.5%	-0.1%	-0.4%	26.1%	-0.2%	-1.1%	13%	113%	73%	0.00	0.00	0.00
dV SP	13.2%	-3.9%	-2.8%	3.2%	0.2%	-1.4%	15.4%	17.4%	-9.3%	-50%	25%	18%	0.00	0.00	0.00
Distance SP	-4.1%	-5.6%	-3.0%	3.8%	4.8%	-3.1%	12.5%	1.7%	-5.5%	-88%	-50%	45%	0.00	0.00	0.00
Distance LP	-1.4%	-7.3%	-3.8%	3.1%	0.5%	-1.8%	12.8%	0.6%	-4.4%	-75%	75%	127%	0.00	0.00	0.02
Time SP	-0.8%	3.1%	-0.1%	3.0%	3.9%	-0.8%	12.0%	14.1%	-2.5%	0%	25%	55%	0.00	0.00	0.00
Time LP	-6.3%	-6.8%	-1.8%	1.0%	1.8%	-1.7%	4.0%	6.7%	-5.1%	0%	13%	82%	0.00	0.00	0.01
OFF	325.4%	152.7%	72.4%	-24.9%	-27.4%	-33.2%	-100.0%	-100.0%	-100.0%	35550%	54350%	58355%	0.49	0.50	0.50

other hand, the weighting methods developed could have a small effect on the MACC present in the simulations. Or weighting could cause decreased deviation in some conflicts, while it causes increased deviation in other conflicts, resulting in a low net gain or loss.

It should be noted that large outliers are present, with either a smaller or much larger distance flown. Aircraft leaving the experiment area due to conflict resolution, fly in total a larger distance than planned, but part of this is outside the experiment area. Therefore, the flown distance in the experiment area is smaller than the planned distance. The much larger distance flown by some aircraft is the result of a chain of conflict resolution. During the on-route phase, an aircraft deviates from its planned path as part of conflict resolution. While it is in conflict, the aircraft again needs to deviate further from its path due to a new conflict. This may be repeated several times. When all conflicts are resolved, the total deviation from the path may be large, the aircraft now reverts back to the original path, during which the aircraft heading can have a large angle with the original path, increasing the chances of a new conflict which needs to be resolved at a larger offset of the intended path. This process causes an oscillation around the original path and a large extra distance flown, as visualized in fig. 6.4. At higher distances the outliers are larger, as the possibilities of a chain reaction as described are larger and are seen for all weights. The large deviations are caused by sequential conflicts, which are not necessarily MACC but can be two aircraft conflicts as well. At this point, the effect of weights is limited to decrease the deviation per MACC, for the developed weights, this is not sufficient to prevent large outliers.

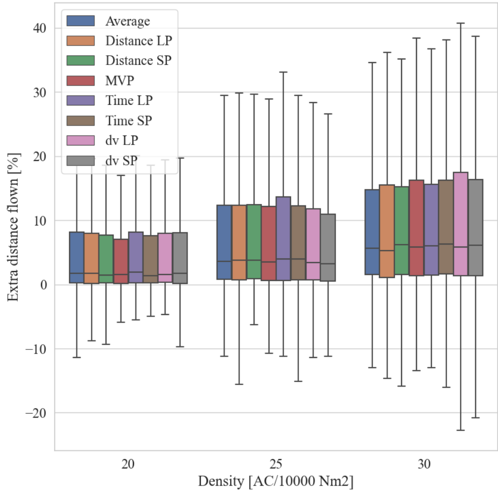
To decrease the deviation of outliers, a different approach might be needed, one that does not look at improving MACC in itself but rather sees them as part of an obstacle on the route. Weights could, for example, include the heading to the next waypoint, this however comes at the risk of reduced resolution activities and therefore increased risk of LoS. The oscillation could potentially also be decreased by solving the conflict by directly reverting back to the original path, if that is possible. The aircraft basically oversolves the conflict to head back to its path. This only works when the conflict resolution is in the direction of the next waypoint. If the conflict resolution would be in the different direction, the conflict resolution efforts of the other aircraft would prevent the conflict from being solved, like the under prioritized aircraft in the case of undersolving section 3.4.1.

6.2. Conflict Results

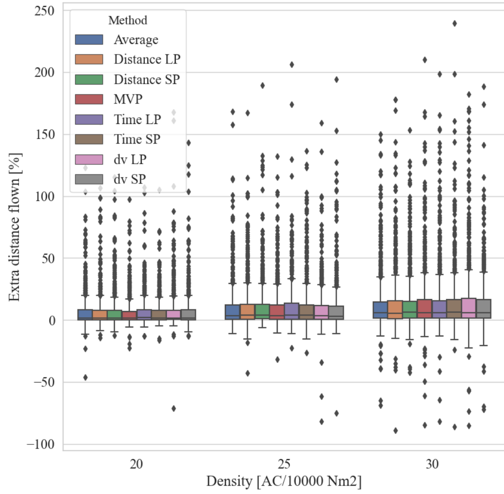
In this section, the MACC performance is analysed on a conflict base. First, the deviation is discussed in section 6.2.1. Then the number of weighted iterations per conflict is discussed in **??**. The total number of iterations needed for a conflict are discussed in section 6.2.3. Finally, the results are concluded in chapter 6.

6.2.1. Deviation MACC

In this subsection, the deviation per conflict, which were part of a MACC is analyzed. The deviation per aircraft per conflict is calculated as discussed in section 3.1 and shown in fig. 6.5. Thus, this figures show the path deviation of the aircraft for resolving a particular conflict, if at some point during the conflict the aircraft was part of a MACC. Therefore, if a single path deviation solves two conflicts, the deviation will be represented twice in the figure.



(a) The extra distance flown per aircraft with respect to the planned route without outliers



(b) The extra distance flown per aircraft with respect to the planned route with outliers

Figure 6.3: The extra distance flown per aircraft with respect to the planned route. No clear effect of the weighted algorithms is seen.

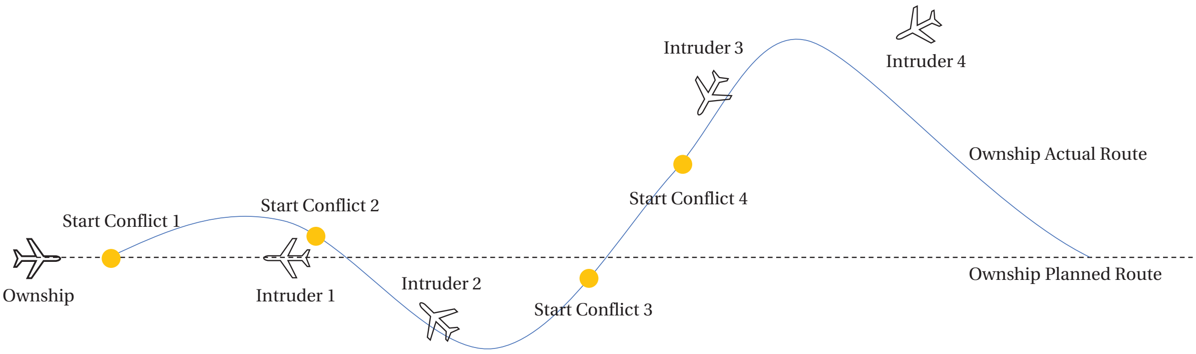
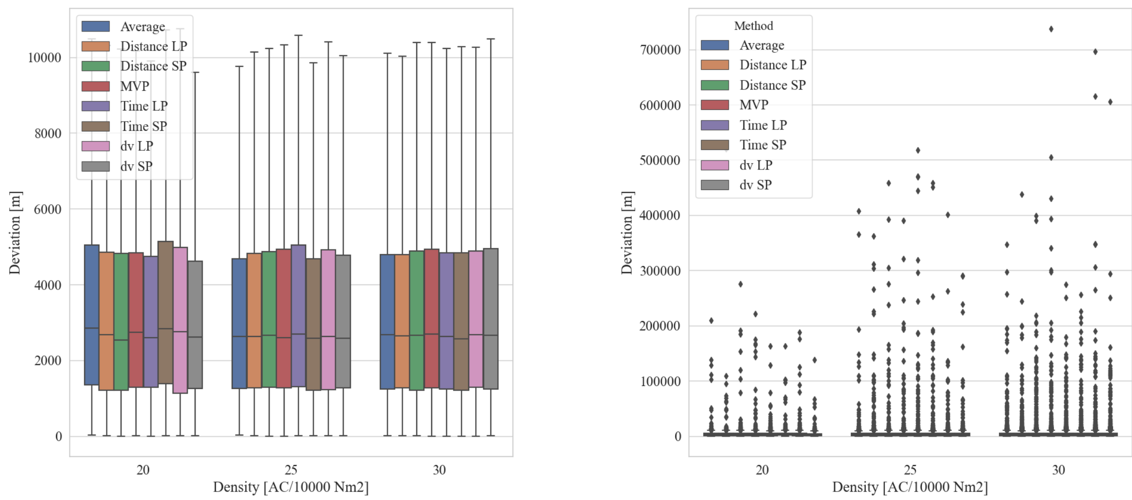


Figure 6.4: A schematic overview of the Ownship route due to conflict resolution compared to the planned route. Consecutive conflicts prevent the ownship from reverting back to the planned route and cause increasing path deviation.

The results show no clear difference in deviation per weight and large outliers are present, similar to the extra distance per flight. The lack of difference in deviation within the box can be because the conflict is only part of a MACC for a low number of iterations. Then, the potential effects of weights are small in those cases. Another reason could be that the weights have little effect on the MACC in this simulation. Or weighting could cause decreased deviation in some conflicts while it causes increased deviation in other conflicts, resulting in a low net gain or loss.

The large deviations can be driven by a long conflict time or larger maneuver. Both actions could be driven by poor conflict resolution or by the effect of secondary conflicts. In chapter 3, the conflicts were reviewed from the ownship perspective, in case of undersolving, the intruders strongly cooperated in the resolution activities. When the resolution of the intruders would also be limited by other conflicts, the resolution maneuvers of all aircraft are limited and therefore it might take longer to find a conflict free trajectory. Long conflict time is not necessarily driven by a MACC, shallow angle conflicts can have a significant contribution to this as well. It is also possible that the aircraft get in conflict for a second time, then the measures would false indicate poor conflict resolution. Although outliers are seen for every method and the reason for the outliers is not quite clear, decreasing the deviation of those outliers has a large impact on their flight path. Therefore, it will be interesting to further investigate the drivers of these large deviations and to investigate what the potential impact of weights could be. This will be further discussed in chapter 7.



(a) The path deviation per aircraft per conflict which has been part of a MACC at any moment during the conflict without outliers

(b) The path deviation per aircraft per conflict which has been part of a MACC at any moment during the conflict with outliers

Figure 6.5: The path deviation per aircraft per conflict which has been part of a MACC at any moment during the conflict. No clear effect of the weighted algorithms is seen.

6.2.2. The number of weighted iterations per conflict

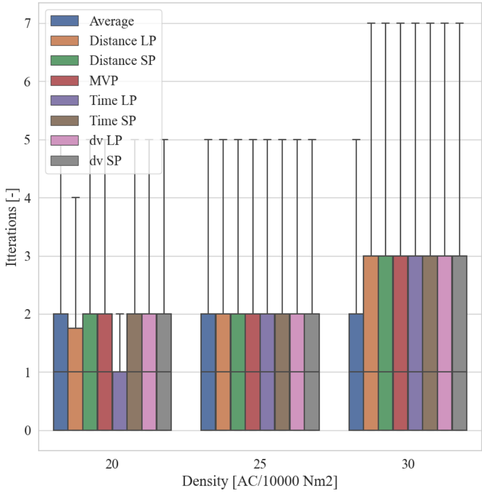
The number of iterations for solving a conflict while it is part of a MACC, is shown in fig. 6.6. This shows the number of iterations where the avoidance vectors were weighted. Conflicts which have not been part of a MACC are not included here. It should be noted that the figure shows the number of iterations per conflict part of a MACC. Thus, if an ownship conflicts with two intruders and it takes multiple iterations to solve both conflicts, this result will be shown for both conflicts. MACCs involving more aircraft are more likely to need more iterations before finding a conflict free path, as the chances are bigger that there is no direct solution possible as is the case with section 3.4.2. Thus, a larger cluster of aircraft in conflict may need more iterations to resolve and are represented for each conflict separately in the figure. The total number of iterations needed to solve a conflict which is part of a MACC is shown in fig. 6.6. Also here, the effects of the various methods are not clearly seen.

It is noticed that the total number of iterations to solve a conflict is much higher than the part in which weightings play a role. A large part of the conflicts which are part of a MACC, are only part of a MACC for a small number of iterations. Thus, the weightings are only influencing the conflict resolution and therefore the trajectory of an aircraft for a small number of iterations. Since only limited maneuvering is possible per iteration and the weightings are only applied to a relative small part of the total resolution, the effects of weighting remain small. The MACC part is probably small as one of the conflicts part of the MACC is already partly solved and only a small intrusion remains when the third aircraft enters the conflict, therefore few iterations are left to solve this conflict. This small effect which a weight has on a conflict, can explain the little effect of the weights have on the deviation.

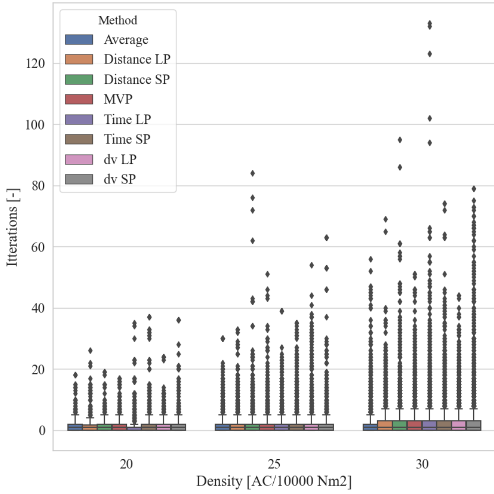
The large outliers indicate poorly resolved conflicts, as discussed section 6.2.1. In the second part of this research, the opportunity for improvements will be investigated, as is discussed in chapter 7

6.2.3. Time in Conflict

The time between the first and last conflict resolution activity per multi-aircraft conflict is shown in fig. 6.7. In a simple conflict which is not surrounded by traffic, this would equal the time needed to solve the conflict,



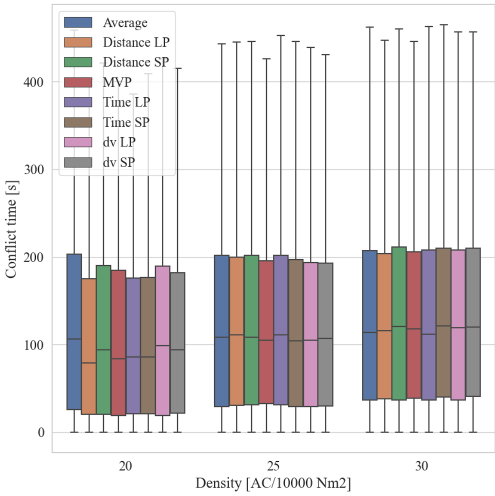
(a) The number of iterations to solve a conflict while the ownship part of a multi-aircraft conflict without outliers



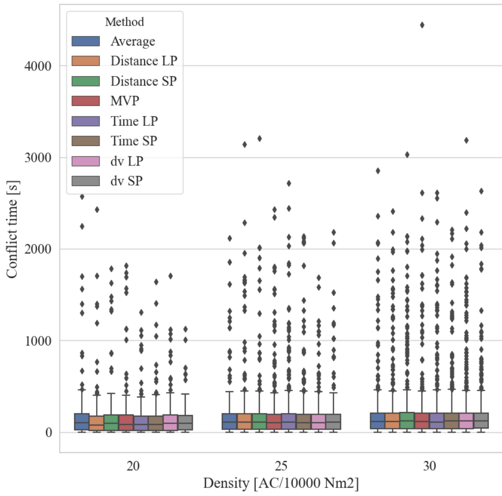
(b) The number of iterations to solve a conflict while the ownship part of a multi-aircraft conflict with outliers

Figure 6.6: The number of iterations to solve a conflict while the ownship part of a multi-aircraft conflict. No clear effect of the weighted algorithms is seen.

i.e., the number of iterations multiplied by the timestep. In cases where there is a lot of traffic, aircraft can be on a conflict free path after conflict resolution, but revert back to an older conflict due to conflict resolution of a newer conflict. This explains the largest part of the conflicts which have a duration below 300 seconds, so below the look-ahead time. Some conflicts have a higher lookahead time, this can be the result of a CPA which moves further away due to conflict resolution, for example, in case of shallow angle conflicts. In some situations, it can also be the case that the aircraft get in conflict a second time when reverting back to the original route, after a significant path deviation. Some outliers show very high conflict times, this can be a clear reason for the very high deviations.



(a) The time between the first and last conflict resolution activity per multi-aircraft conflict. without outliers



(b) The time between the first and last conflict resolution activity per multi-aircraft conflict. with outliers

Figure 6.7: The time between the first and last conflict resolution activity per multi-aircraft conflict. No clear effect of the weighted algorithms is seen.

6.3. Conclusions

In this section, the results of the airspace simulations proposed in chapter 5 are discussed. It was seen that all methods performed very similar in the 75th percentile for all metrics tested when analysed per conflict. Additionally, all methods showed large outliers, increasing over density. At a system level, the number of repetitions per density were limited to three and the differences were small. Therefore, it could not be concluded which, if any, of the tested methods performs best.

There could be a variety of reasons for the small differences in performance seen, as listed below.

(A) The effects of weights on MACC resolution are small because the number of iterations in which an aircraft is part of a MACC is too low to make a significant impact.

(B) The categorisation does not represent all conflicts well in a large simulation, therefore the developed weights can have a smaller impact than expected.

(C) The performance in some conflict situations is better compared to the unweighted MVP algorithm, while in other situations it is worse. Resulting in a similar average for all algorithms.

(D) Thus far, all conflicts are analysed from the ownship point of view and all intruders are assumed to be able to move freely. When the intruders are also in conflict with other aircraft, their movement can be restricted. The effect of those secondary conflicts may limit the intruders movement has not been evaluated, but does have impact on conflict resolution performance.

(E) The number of data points is too low, causing the results to be similar by chance.

(F) The developed weights do perform well in certain conflicts as described in chapter 4, although this does not result in a system level improvement. It could be that the improvements on a system level are washed out by the unweighted single conflicts or by large impact of conflict recovery.

It is also valuable to identify the probable causes of the larger deviations, as those might provide significant opportunities to improve. A large deviation results from a long conflict time as the traveled distance is larger, or from significant heading changes. Possible drivers are listed below.

(a) In cases of undersolving, the conflict time can get large when the intruders are also in conflict with multiple aircraft and therefore also neglect to fully resolve the conflict.

(b) A shallow angle conflict drives a large conflict time.

(c) The aircraft get in conflict for a second time, then the measures would false indicate poor conflict resolution.

7 Research proposal second experiment phase

As the results of chapter 6 showed little performance variation in the 75th percentile, the potential gain of using weights in general and specifically developed weights will be investigated in the second part of this research. In addition, the second part of the conflict will investigate what the drivers of the large deviations are and try to reduce the deviations by weighting MACC where possible. The steps to be taken are discussed in section 7.1, the planning is shown in appendix A.

7.1. Steps to be taken

To get more insight into the small performance difference and to identify the drivers, one more loop is made through the workflow diagram, fig. 1.1. The steps made are intended to assess the statements made in the conclusions of the results, section 6.2. Below, the details of the research activities for the second phase are explained.

Research Activity 2
Develop and run experiment scenarios
The current experiments do not provide enough information to conclude on the performance of the developed methods. The performance could be analysed in more detail when the same conflict situations are compared. An additional set of conflict situations can help to identify the potential impact of weights. A representable set of MACC situations is created by distilling all MACC from the simulations discussed in chapter 6. To limit the size, only the MACC in the simulations using the MVP algorithm are used at first. The MACC will be composed as at the start of the MACC, first without other traffic and second with all traffic within the lookahead time. This is to also include the effect of other conflicts on intruders and the effect of other traffic in general.

The situations are simulated using the developed weighted algorithms and the unweighted MVP algorithm for conflict resolution. The measurements include the number of iterations needed, the path deviation, LoS, and the k_{cdr}.

Research Activity 3
Analyse and evaluate the experiment results
The first step of the analysis is to compare performance of the algorithms per measure. It is expected that using those test under performing weighting methods can be identified. Those will be disregarded in the remainder of this study.

The second step of the analysis is to identify in which conflict situation improvements can be made. That are the conflicts which show poor performance in terms of efficiency, stability, or safety and a high number of iterations can be improved by a weighting. Using this method, the potential effect of weights can be identified.

Research Activity 4
Categorise multi-aircraft conflict resolution behaviour
The current categorisation is evaluated based on the results of the previous step, when necessary a further division of categories is made, based on the number of aircraft, conflict angles, intrusion, distance, and time to CPA.

Research Activity 2
Develop and run experiment scenarios Per category, conflict situations are randomly generated within the boundaries of the categorisation. The situations are simulated using the MVP algorithm combined with the remaining weighting methods for conflict resolution.

Research Activity 3
Analyse and evaluate the experiment results
The conflict resolution mechanisms are evaluated and explained. Subsequently, drivers of poor performance are identified.

Research Activity 5
Develop a weighted MVP algorithm
The remaining weighting methods are modified where necessary, to improve conflict resolution of the poorly resolved conflicts.

Research Activity 2
Run experiment scenarios
The performance of the weighing methods is analysed by simulating air traffic. To increase significance, 20 repetitions are used at this stage. The scenario generation, measures and other variables are as discussed in chapter 5.

Research Activity 3 and 6
Conclude on the opportunities to improve MACC resolution by weighting the individual conflict resolution maneuvers.
The performances of the developed weights are evaluated. Conclusions will be drawn on the potential impact on MACC resolution and conflict resolution in general of weights and the improvements made by the weights developed.

8
Conclusions

The desire to fly more direct routes has grown within the aviation industry, with the desire of decreasing cost, pollution, and delays. The concept of free flight moves the responsibility of safe separation from centralized ATM organisations to the aircraft on-board. To ensure self-separation, conflict detection and resolution algorithms are needed to notice future loss of separation and suggest an avoidance maneuver. The Modified Voltage Potential is such a conflict detection and resolution algorithm. It determines conflicts based on nominal state propagation, subsequently a tactical and implicitly coordinated avoidance vector is calculated, where needed, based on the force-field analogy. The Modified Voltage Potential works well for most simple conflicts. This report is the first part of an investigation into the conflict resolution mechanics in multi-aircraft conflicts is investigated and the possible improvement of weighting pair-wise avoidance vectors.

To create an overview of the possible mechanics of multi-aircraft conflict resolution, two categories were distinguished. When all avoidance vectors suggest a maneuver to the same side of the aircraft, the instantaneous sum of the vectors is larger than necessary to solve the conflict, this is called oversolving. When the vectors suggest maneuvering to the various sides, the sum does not directly result in a conflict path, this is called undersolving. To solve this conflict, the situation needs to be reevaluated a couple of iterations. It is shown that reevaluating the situation with a one second time step comes with benefits in terms of solution efficiency, both in case of oversolving and undersolving.

The analysis of the multi-aircraft conflicts in itself showed that improvements could be to decrease path deviation or the destabalizing effect on the airspace. Seven methods were suggested to weight the avoidance vectors before summing. Two weights were developed based on the expected time to loss of separation, two weights were developed based on the distance between the aircraft, two weights were developed to prioritize a maneuver to one side, or the other based on the size of the avoidance vector and one weight took the average rather than the sum

It was expected that the developed methods would show somewhat opposite performance in terms of efficiency or safety, when used as conflict resolution method in a fast-time simulation of the airspace in free flight. The results shown, however, were very small for the largest part of the multi-aircraft conflicts and aircraft. However, large outliers were shown for all methods. It is expected that the small effect on large parts is caused by a low number of iterations where multiple avoidance vectors are summed. Since the effect of weights is limited to those methods, the effects remain small. The large outliers are. caused by long conflicts time due to poor conflict resolution.

In the second half of this research, efforts are made to identify the proportion on which weights can have a significant effect. Those multi-aircraft conflicts are further broken down in subcatagories if needed and the resolution performance of the developed methods is analysed. If needed, further developments on the methods are made, before more elaborate airspace simulations will be performed

A

Gantt Chart

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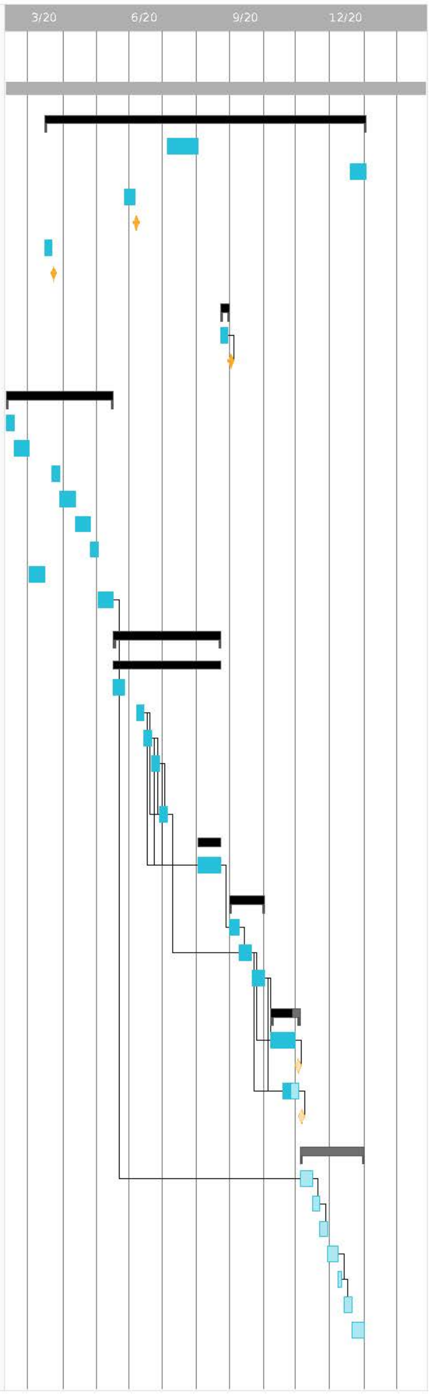
Holidays and other thesis deviation	**16/03/20**	**01/01/21**	**100%**
Summer holiday	06/07	31/07	100%
Christmas break	21/12	01/01	100%
Noise exam studying	27/05	04/06	100%
Noise exam	04/06	04/06	100%
Prepare Case interview	16/03	20/03	100%
Case Interview	20/03	20/03	100%
Research Methodologies	**24/08/20**	**31/08/20**	**100%**
Writing report	24/08	28/08	100%
Milestone	31/08	31/08	100%
Literature Study	**10/02/20**	**15/05/20**	**100%**
Research ASAS and free flight	10/02	14/02	100%
Research MVP	17/02	28/02	100%
Research other Methods	23/03	27/03	100%
Safety	30/03	10/04	100%
Stability	13/04	24/04	100%
Efficiency	27/04	01/05	100%
Familiarize with Bluesky	02/03	13/03	100%
Simulations	04/05	15/05	100%
Develop Weighted Algoritms	**18/05/20**	**21/08/20**	**100%**
Investigate Strengths and weakn...	**18/05/20**	**21/08/20**	**100%**
Develop a tool to analyse solution ef...	18/05	26/05	100%
Investigate areas of strength/weak...	08/06	12/06	100%
Define driving criteria of strength/w...	15/06	19/06	100%
Catogorise conflict scenarios	22/06	26/06	100%
Develop test scenarios	**-**	**-**	**0%**
Develop test scenarios	29/06	03/07	100%
Develop weighted sum	**03/08/20**	**21/08/20**	**100%**
Develop weighted sum	03/08	21/08	100%
Verify developed solutions	**01/09/20**	**01/10/20**	**100%**
Implement weights developed	01/09	08/09	100%
Verification	09/09	18/09	100%
Evaluate results	22/09	01/10	100%
Prelim	**08/10/20**	**03/11/20**	**75%**
Write preliminary report	08/10	29/10	100%
Hand In preliminary report	30/10	30/10	0%
Preperare presentation	20/10	02/11	50%
Prelim	03/11	03/11	0%
Experiments	**04/11/20**	**31/12/20**	**0%**
Distil MACC and analyse effects of we...	04/11	13/11	0%
Catagorisation and scenario develop...	16/11	20/11	0%
Perform simulations and analysis	23/11	27/11	0%
Weight development	30/11	08/12	0%
Large scale simulation	09/12	10/12	0%
Result analysis	15/12	21/12	0%
Delay	22/12	31/12	0%



Finalisng Thesis	**01/01/21**	**25/02/21**	**0%**
Write final report	01/01	12/01	0%
Submit Draft	13/01	13/01	0%
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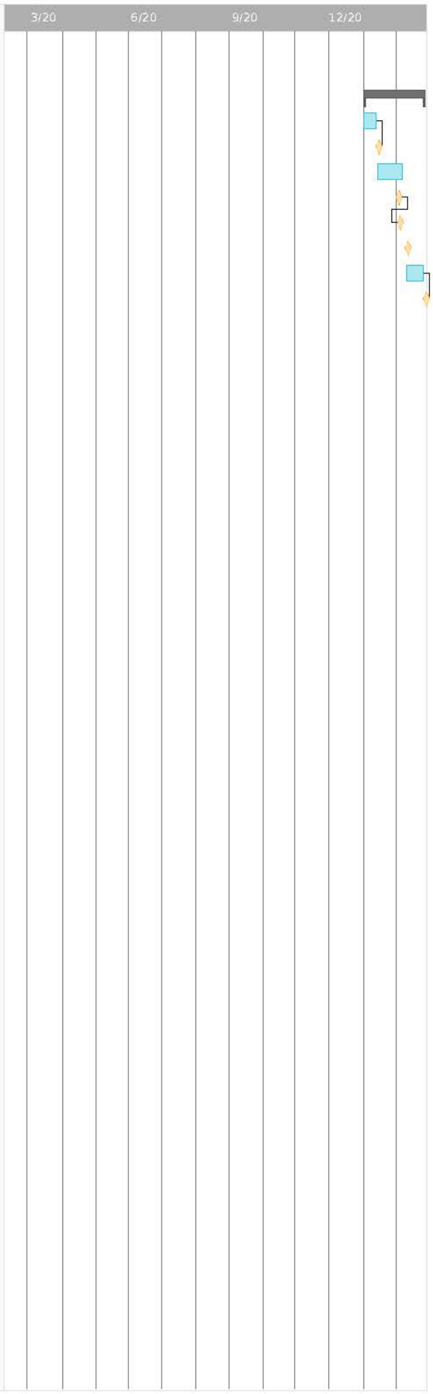
Thesis hand in	09/02	09/02	0%
Prepare defence and final presentation	10/02	24/02	0%
Defence	25/02	25/02	0%



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