

Extending the Modified Voltage Potential algorithm for use in converging traffic flows

R. Jacobse

21 September 2020

Extending the Modified Voltage Potential algorithm for use in converging traffic flows

MASTER OF SCIENCE THESIS

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

R. Jacobse

21 September 2020



Delft University of Technology

Copyright © R. Jacobse
All rights reserved.

DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
CONTROL AND SIMULATION

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled “**Extending the Modified Voltage Potential algorithm for use in converging traffic flows**” by **R. Jacobse** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: 21 September 2020

Supervisors:

prof.dr.ir. J.M. Hoekstra

dr.ir. J. Ellerbroek

Reader:

ir. P.C. Roling

Preface

This thesis is the final product which concludes my time as a student here in Delft. The road to getting here was tough and challenging at times but proves to be very rewarding in the end. During my time here I have been fortunate enough to make friends in various places. I would like to thank all of them for (in no particular order): the great holidays, the parties, the drinks, the coffee breaks, the game nights and most of all the many small moments and memories.

I also would like to thank my daily supervisor Joost Ellerbroek for his insights and ability to approach problems from different angles during our many meetings. On more than one occasion his advice has helped me find my way through the tough parts of this project. Furthermore, I would also like to thank Jacco Hoekstra for his enthusiasm and ability to inspire that led me choose to this thesis topic in the first place.

Lastly, and most importantly, I would like to thank my parents and my brother for all of their love, help and support in all possible ways through the years. Knowing that they stood behind me helped me to make it to where I am today.

Ruben Jacobse
Delft, 21 September 2020

Contents

Preface	v
List of Tables	ix
List of Figures	xii
List of Abbreviations	xiii
List of Symbols	xv
 I Scientific article	 1
 II Appendices	 19
A Conflict location figures	21
A-1 No conflict resolution	22
A-2 Modified Voltage Potential Method	23
A-3 Velocity Averaging Method	24
A-4 GV-SPD Method	25
A-5 GV-ZONES Method	26
A-6 GV-RINGS Method	27
A-7 GV-GRID Method	28
 III Preliminary report (already graded)	 29
1 Introduction	31
1-1 Research goals	32
1-2 Outline of this report	33

2	Literature review	35
2-1	Airspace restrictions and corridors	35
2-1-1	Types of airspace restrictions	35
2-1-2	Airspace corridor types	36
2-2	Conflict prevention, detection, and resolution	38
2-2-1	Conflict and intrusion definitions	38
2-2-2	Conflict Prevention, Detection, and Resolution	39
2-2-3	Classification systems for different conflict handling methods	39
2-3	Automatic Dependent Surveillance-Broadcast	41
2-4	Conflict handling methods for aircraft-to-aircraft conflicts	42
2-4-1	Modified Voltage Potential	42
2-4-2	Velocity Obstacle-based methods	44
2-5	Conflict handling methods for aircraft-to-area conflicts	48
2-6	Motion behavior rules	49
2-6-1	Reynolds' motion behavior hierarchy	49
2-6-2	Geovectoring	51
2-7	Relevant previous work extending the MVP method	52
2-7-1	Extension of the MVP method with Leader-following behavior	52
2-7-2	Extension of the MVP method with swarming behavior	55
2-8	The Metropolis project	57
2-9	A capacity model for self-separation methods	59
2-10	Conclusions	60
3	Methodology	61
3-1	Research scope and assumptions	61
3-2	The BlueSky simulation environment	63
3-3	Research setup	63
3-3-1	Airspace scenario selection	63
3-3-2	Area avoidance method	65
3-3-3	Steering rule hierarchy	66
4	Experiment proposal	69
4-1	Control variables	69
4-2	Independent variables	70
4-2-1	Additional steering rules	70
4-2-2	Traffic level	71
4-2-3	Aircraft-to-area conflict look-ahead time	71
4-2-4	Airspace geometry	72
4-3	Dependent Variables	72
4-4	Experiment design	75
4-4-1	Experiment Phase I	75
4-4-2	Experiment Phase II	75
	Bibliography	77

List of Tables

2-1	Summary of properties of different corridor types.	36
2-2	Conflict resolution method used based on conflict direction and status of ownship and intruder.	53
2-3	Weight values used to calculate the final resolution vector in the Swarm Augmented Modified Voltage Potential method.	56
4-1	Aircraft types, average speeds and percentages of traffic as used in all experiments.	69
4-2	Traffic levels used in the experiment with the approximate number of aircraft simulated per hour and approximate traffic density.	71
4-3	Aircraft-to-area conflict look-ahead time levels.	71
4-4	Levels and corresponding values for airspace geometry parameters.	72
4-5	Summary of the safety, efficiency, stability, and capacity metrics.	74

List of Figures

A-1	Conflict and loss of separation locations without conflict resolution.	22
A-2	MVP method conflict and loss of separation locations	23
A-3	Velocity averaging method conflict and loss of separation locations	24
A-4	Geovectoring method 1 conflict and loss of separation locations	25
A-5	Geovectoring method 2 conflict and loss of separation locations	26
A-6	Geovectoring method 3 conflict and loss of separation locations	27
A-7	Geovectoring method 4 conflict and loss of separation locations	28
2-1	Examples of different types of airspace restrictions that can create corridors . . .	37
2-2	The PZ around an aircraft extends 5 NM in all horizontal directions and 1000 ft in both vertical directions	38
2-3	Geometry of a conflict as used in the MVP method	43
2-4	The relation between the Collision Cone and Velocity Obstacle	44
2-5	Visualization of the construction of the SSD	45
2-6	Examples of solutions based on different coordination rules as proposed by Balasooriyan.	46
2-7	Visualization of conflict types and relationship with the VO used by the SVO method	47
2-8	Visualization of a minimum turn rate maneuver prescribed by the SVO method. .	47
2-9	Collision Cones defined by irregularly shaped static obstacles.	49
2-10	Reynolds' motion behaviors hierarchy	50
2-11	Visualization of the relationship between geofencing, geocaging, and geovectoring concepts	51

2-12	Visual representation of the geovector allowable ranges of the velocity vector components.	52
2-13	Conflict resolution prescribed by the leader-following method	54
2-14	Averaging of the velocity vectors in the velocity averaging process	55
2-15	Calculation process for the velocity vector pointing towards the center of the flock	56
2-16	The four airspace structure concepts and their constraints on aircraft's degrees of freedom	57
3-1	Generalized experiment area.	64
3-2	The three airspace concepts based on the Metropolis findings.	65
3-3	Example of an aircraft that is in conflict with an airspace restriction.	66
3-4	Steering rule hierarchy split into CR, CP and route following categories.	67

List of Abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast
ATC	Air Traffic Control
ATCo	Air Traffic Control officer
ATM	Air Traffic Management
C&S	Control & Simulation
CAMDA	Capacity Assessment Method for Decentralized Air Traffic Control
CC	Collision Cone
CD	Conflict Detection
CD&R	Conflict Detection & Resolution
CP	Conflict Prevention
CPA	Closest Point of Approach
CR	Conflict Resolution
CTR	Controlled Traffic Region
DEP	Domino Effect Parameter
DUT	Delft University of Technology
FIS-B	Flight Information Services-Broadcast
GUI	Graphical User Interface
IAS	Indicated Air Speed
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
LNAV	Lateral Navigation
LoS	Loss of Separation
MVP	Modified Voltage Potential
NextGen	Next Generation Air Transportation System
NM	Nautical Mile
NOTAM	Notice to Airmen
PAV	Personal Air Vehicle
PZ	Protected Zone
RAA	Restricted Airspace Area

RPK	Revenue Passenger-Kilometer
SESAR	Single European Skies ATM Research
SRS	SIMONA Research Simulator
SSD	Solution Space Diagram
SSEP	Self-Separation
SSR	Secondary Surveillance Radar
SUA	Special Use Airspace
SVO	Selective Velocity Obstacle
TIS-B	Traffic Information Services-Broadcast
TMA	Terminal Manoeuvring Area
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UTM	UAS Traffic Management
VFR	Visual Flight Rules
VIP	Very Important Person
VO	Velocity Obstacle
WHA	Weather Hazard Area

List of Symbols

Greek Symbols

α	Relative heading difference
η	Efficiency
ρ	Traffic density
χ	Heading angle

Roman Symbols

A	Airspace area
C	Number of conflicts
d	Distance
k	Airspace structure effects parameter
L	Number of traffic layers
n	Number of conflicting aircraft
N	Total number of instantaneous aircraft
p	Conflict probability
R	Minimum separation distance
$\mathbf{s}$	Displacement vector
t	Time
T	Time interval
$\mathbf{T}$	Thrust vector
V	Velocity magnitude
$\mathbf{V}$	Velocity vector
W	Work performed

Part I

Scientific article

Can the Modified Voltage Potential algorithm be extended for use in converging traffic scenarios?

R. Jacobse (MSc Student)

Supervisors: Prof.dr.ir. J.M. Hoekstra, Dr.ir. J. Ellerbroek

Section Control & Simulation, Department Control & Operations, Faculty of Aerospace Engineering,
Delft University of Technology, Delft, The Netherlands

Abstract—The maximum workload for air traffic control officers is a key constraint on the capacity of the airspace system and subsequent growth of air traffic movements. One research direction that aims to increase this capacity is the Free Flight concept in which air traffic control is removed and aircraft themselves take over its responsibilities. The Modified Voltage Potential (MVP) algorithm is an implementation of this concept. However, its use in the presence of airspace restrictions has not been studied extensively. This paper investigates five possible extensions to enable its usage in such situations by adding extra steering rules and creating a hierarchy of steering behaviors. One concept adds a velocity averaging rule based on the relative aircraft positions and the other four add geovectoring rules based on their absolute positions. The concepts are tested using fast-time simulations to compare their effects on safety, efficiency, stability, and capacity metrics. The experiment shows that three of the concepts using geovectoring perform better than the baseline MVP method whereas the velocity averaging concept performs worse on some safety and stability metrics. Further research is suggested to study the interaction effects between the different rules in the steering behavior hierarchy.

Index Terms—Modified Voltage Potential (MVP), Corridor, Airborne Separation Assurance System (ASAS), Self-Separation

I. INTRODUCTION

THE number of commercial flights has increased exponentially over the past decades. In 2018 the International Civil Aviation Organization (ICAO) reported an average annual growth of 5.4% in the total number of Revenue Passenger-Kilometers (RPKs) flown over the period from 1995 to 2015 [1]. In this report ICAO predicts a further RPK growth of 4.1% per year between 2015 and 2045. More recently, in its 2020 forecast the US Federal Aviation Administration (FAA) predicted an international RPK growth of 3.0% per year between 2020 and 2040 [2]. It is noted that the forecast does not include the effects of the COVID-19 pandemic. Its economic impact introduces a lot of uncertainty in the short term but it is expected that this is temporary and that economic growth will resume afterwards. Besides conventional aircraft the number of Unmanned Aerial Systems (UAS) has also shown an increasing trend. Integrating this traffic into the Air Traffic Management (ATM) system further increases the number of movements and adds additional complexity [3]–[5].

Both Eurocontrol via their Single European Skies ATM Research (SESAR) program and the FAA via their Next Generation Air Transportation System (NextGen) program are researching various different approaches to solving the

problems caused by the pressure on the airspace system [6], [7]. One of the most important constraints on airspace capacity is the maximum workload of the Air Traffic Control Officer (ATCo) [8], [9]. Currently, the airspace is divided into sectors inside of which all traffic is handled by an ATCo. To reduce their workload these sectors are structured such that the complexity of traffic flows is minimized. This however does lead to less efficient routing, increased flight delays, and increased emissions.

A proposed approach towards solving this capacity issue is the Free Flight (FF) concept in which the centralized responsibilities of Air Traffic Control are decentralized by transferring them to the aircraft that will then use self-separation [10]. Where in the current ATM system the ATCo is the only one to have a situational overview new techniques such as Automatic Dependent Surveillance-Broadcast (ADS-B) allow aircraft to send and receive real-time status updates without needing a ground station [11]. The implementation of the FF concept is subject of ongoing research and various methods for Conflict Detection (CD), Conflict Prevention (CP), and Conflict Resolution (CR) have been proposed. An overview of research efforts and a qualitative comparison of various proposed CD- and CR-methods is given by Kuchar & Yang [12].

One promising method is the Modified Voltage Potential (MVP) algorithm proposed by Hoekstra et al. in 1998 as an adaptation of an earlier method proposed by Eby in 1994 [13], [14]. The method works by having an aircraft calculate a resolution vector for each aircraft they are in conflict with and then uses vector summation over the results for its conflicts to obtain a final avoidance vector. The algorithm prescribes action only for conflicts between aircraft and does not consider other types of obstacles.

One type of situations in which the use of the MVP method has not yet been studied extensively are scenarios where airspace restrictions force traffic flows to converge in certain regions. Examples of situations in which this can occur are sector boundaries, the presence of military special use airspaces, weather hazard areas, controlled airspaces or ground obstacles [15]–[18].

In 1997 Reynolds published a motion behavior hierarchy and gave an overview of motion steering behaviors for autonomous actors [19]. In that paper a number of simple basic behaviors are described that can be combined to give agents more complex behavior patterns. Although its focus lies on

video game characters its principles can also be applied to other types of agents. Both Kieskamp and Maas have used some of these behaviors to extend the MVP algorithm with different goals [20], [21].

This study uses fast-time simulations in the BlueSky ATM simulator [22] to compare several concepts in which additional steering rules are added to the MVP method. The goal of this study is to find out whether these concepts can be used to improve the performance of the MVP algorithm in a converging traffic situation caused by airspace restrictions. The additional steering rules are divided into two categories: those that depend on aircraft positions relative to each other and those that depend only on their absolute position. Metrics regarding safety, efficiency, stability, and capacity are used to compare the experiment results.

The contents of this paper are laid out as follows: in Section II an overview of relevant previous work is given. The concepts that are studied are introduced in Section IV and the experiment design is presented in Section V. The results of the experiment are given in Section VI and are discussed in Section VII. Finally, in Section VIII the conclusions are given.

II. PREVIOUS WORK

Several works that were briefly referred to in the previous section that are of importance to the research in this paper are treated in more detail here.

A. Modified Voltage Potential method

The MVP self-separation method is the main building block upon which the current research is based. It is an adaptation of a method proposed by Eby, who likened his method of self-separating aircraft to similarly-charged particles that exert a repulsive force onto each other [14]. Subsequently, Hoekstra et al. slightly changed the method by which the resolution vector is calculated, resulting in the MVP algorithm [13].

The MVP method uses the notion of a Protected Zone (PZ) around each aircraft in which no other traffic is allowed to enter. This 3-dimensional PZ is defined by a radius around the aircraft in the horizontal plane and a constant distance in the vertical plane. The algorithm uses nominal state extrapolation to predict aircraft future positions. Two aircraft that are predicted to enter each other's PZ at some future moment are said to be in conflict. When two aircraft are inside each other's PZ they are said to be in Loss of Separation (LoS).

When a conflict is detected for a given 'ownship' the MVP method computes the position of the intruding aircraft at the closest point of approach. It then calculates the smallest resolution vector perpendicular to its current velocity vector that steers clear of the intruder's PZ at that time. This resolution vector is added to the ownship's current velocity vector to result in a new velocity vector that solves the conflict. The intruding aircraft applies the same rules and is guaranteed to turn in the opposite direction of the ownship [23]. The conflict geometry is shown in Fig. 1 and the avoidance vector $\mathbf{V}_{avoid}(t)$ is given by Eq. 1:

$$\mathbf{V}_{avoid}(t) = \frac{\mathbf{CO}'}{t_{cpa}} \quad (1)$$

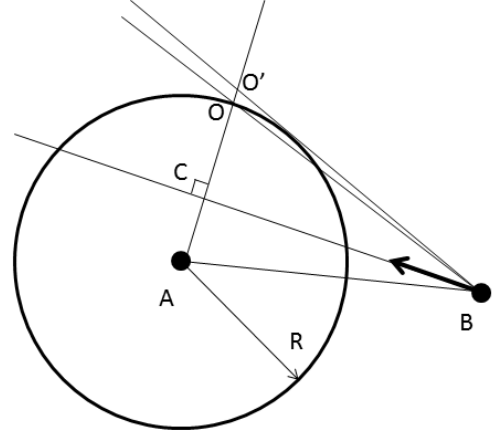


Fig. 1. MVP method conflict geometry with ownship B and intruder A whose PZ has radius R [24, p. 59]. The arrow shows the relative velocity of B with respect to A.

Here, $\mathbf{CO}'$ is the distance vector perpendicular to the current velocity vector required to avoid the PZ and t_{cpa} is the time to the closest point of approach. The equation is a function of time because it depends on the conflict geometry which changes over time and when the aircraft start maneuvering.

When an aircraft is in conflict with multiple intruders at the same time the MVP method prescribes that the sum of the individual resolution vectors is added to the current velocity. Thus, in the general case for an aircraft with n conflicting intruders the prescribed velocity $\mathbf{V}_{MVP}$ is given by Eq. 2:

$$\mathbf{V}_{MVP}(t) = \mathbf{V}_{current}(t) + \sum_{i=1}^n \mathbf{V}_{avoid,i}(t) \quad (2)$$

This equation signifies an interesting property of the MVP algorithm: it is always able to produce an resolution vector. However, that vector is not guaranteed to solve all conflicts when an aircraft is in multiple conflicts at once.

B. Area avoidance

In the present ATM system aircraft routes are planned in advance and ATCos ensure that aircraft remain clear of restricted airspace areas and weather hazard areas when present. In the self-separation concept aircraft will need to take evasive action themselves to avoid those areas. In this paper only non-moving airspace restrictions are considered.

A generalized method for avoiding obstacles was proposed by Chakravarthy et al. in 1998 [25]. It defines a Collision Cone (CC) as the area between the tangents from a point to an obstacle. To avoid collision a course that lies outside the CC has to be chosen. When an aircraft takes the role of the moving point this method can be used to avoid non-moving obstacles.

C. Swarming concept

The swarming concept proposed by Maas combines three different steering behaviors: Collision Avoidance (CA),

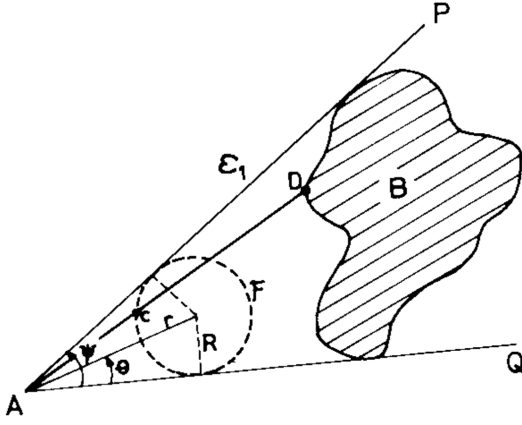


Fig. 2. Collision Cone enclosing an obstacle B from point A [25, p. 568].

Velocity Alignment (VA), and Flock Centering (FC) [21]. The goal is to improve self-separation performance by lowering the number of conflicts and intrusions through reducing the relative velocities between aircraft.

For each of the steering behaviors an new aircraft velocity vector is calculated that the aircraft would need to fly to implement that particular behavior. The CA vector is calculated using the MVP algorithm. The VA vector is found by taking the average velocity of the ownship and nearby aircraft as shown in Fig. 3. The FC vector is calculated by computing the unit vector towards the average position of the ownship and surrounding aircraft and scaling this with the ownship's velocity as shown in Fig. 4. One notable difference with the normal MVP method is that the swarming method can give resolution vectors through VA and FC behavior even if no conflicts are present.

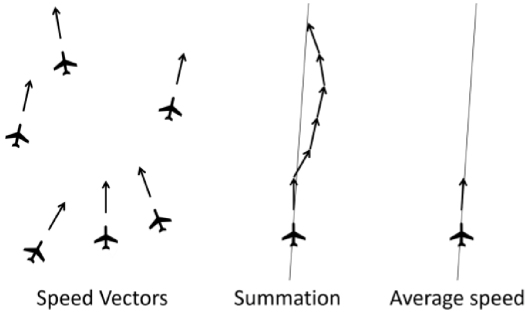


Fig. 3. Velocity Averaging vector calculation process [21, p. 2].

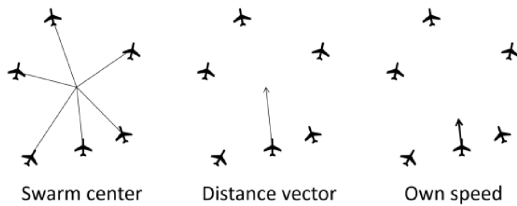


Fig. 4. Flock Centering vector calculation process [21, p. 3].

For any given aircraft the CA vector is calculated whenever

it is in a conflict and the VA and FC vectors are only calculated if nearby aircraft meet a set of criteria to be considered as part of the swarm by the aircraft doing the calculation. Only when all three following criteria are met will a nearby aircraft be considered part of the flock:

- The horizontal distance is less than 7.5 nautical miles
- The vertical distance is less than 1500 feet
- The heading difference is less than 90 degrees

The resulting swarming velocity vector V_{SW} is calculated by taking a weighted average of the V_{CA} , V_{VA} , and V_{FC} velocity vectors with the respective weights 10, 3, and 1 as given in Eq. 3:

$$V_{SW} = \frac{10 \cdot V_{CA} + 3 \cdot V_{VA} + 1 \cdot V_{FC}}{10 + 3 + 1} \quad (3)$$

Maas tested the performance of the swarming algorithm in unconstrained airspace and found that the MVP method performed better than the swarming concept on various metrics. The swarming method generated a higher number of conflicts and losses of separation which was theorized to be caused by its clustering effect where aircraft stick together instead of using the full available airspace.

D. Leader-Following concept

Two related concepts that build upon the MVP algorithm are the Leader-Following (LF) and Leader-Following with Follow-Through (LFFT) methods proposed by Kieskamp in his master thesis [20]. These methods were developed with the aim to improve the traffic flow of self-separating aircraft in the presence of restricted airspaces and extend the MVP algorithm with steering rules based on the leader-following behavior type described by Reynolds.

The methods are slightly more complicated than the MVP method because they distinguish two roles with different behavior rules for aircraft: the leader, and the follower. Which role and set of rules each aircraft in a conflict pair must follow is determined by their relative velocity and conflict geometry. For a more detailed description of these methods the reader is referred to Kieskamp's original thesis.

Although the LF and LFFT methods were proposed for use in scenarios with airspace restrictions the original experiments consisted of only a handful of aircraft thus leading to results of which the validity can be questioned due to small sample size. The methods were considered for more elaborate testing in this experiment but during preliminary analysis it became apparent that in some situations (e.g. a faster aircraft overtaking a slower one) the methods actively caused losses of separation instead of avoiding them. For this reason the LF and LFFT methods were not included in the experiments in this paper.

E. Geovectoring

The geovectoring concept was introduced by Hoekstra et al. in 2018 to increase airspace capacity for high density UAS traffic [26]. Its principles however can also be applied to airspace design for conventional air traffic. A geovector consists of two parts. The first is the geographical area defined by horizontal and vertical limits. The second part is the

restriction to the aircraft's velocity vector $\mathbf{V}_{geo}$ that applies inside the geovectoring area. The generalized form of this restriction takes the form given in Eq. 4.

$$\mathbf{V}_{geo} = \begin{pmatrix} [GS_{min}, GS_{max}] \\ [\chi_{min}, \chi_{max}] \\ [VS_{min}, VS_{max}] \end{pmatrix} = f(lat, lon, altitude) \quad (4)$$

Here GS , χ , and VS are respectively the ground speed, course, and vertical speed components. A geovector restriction can either apply to all or only part of the velocity components. Furthermore, the restriction can either be static or dynamic and change over time.

III. AREA GEOMETRY

One of the conclusions of an earlier study in the Metropolis project's research into airspace structure and capacity for self separation was that the layered airspace concept performed best out of those concepts tested [27]. Based on that finding the research in this paper limits the geometry to the horizontal plane only and thus considers a single layer without vertical traffic movements and interactions. Because the Metropolis layers concept uses different altitudes for different heading ranges the traffic flow in the experiments will be unidirectional and all aircraft are routed from south to north. The traffic altitude chosen for this research is 36,000 feet, which is representative for the cruising altitudes of commercial aircraft. A top-down view of the experiment area that is used in this paper is shown in Fig. 5. The unrestricted airspace can be split into three regions: the rectangular corridor in the middle, the convergence region leading to the corridor on the south side, and the divergence region leading away from the corridor on the north side.

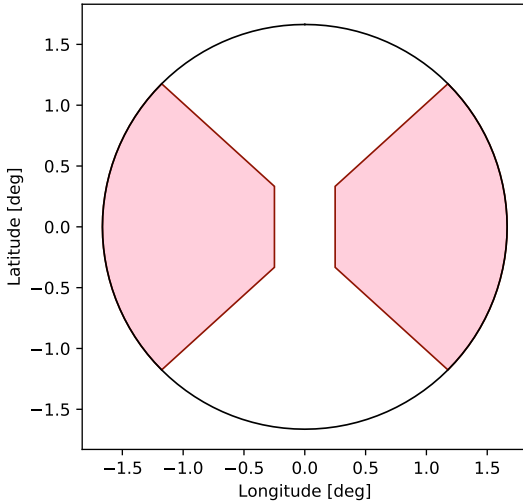


Fig. 5. Experiment area geometry with the airspace restrictions in red.

The circular experiment area has a radius of 100 nautical miles and contains two restricted airspace areas (shown in red) that limit the airspace available to traffic. The rectangular corridor region in the center has a length of 40 nautical miles and a width of 30 nautical miles. The area restrictions are defined such that the experiment area perimeter is divided into

four equal parts. This area geometry is used as basis for all MVP extension concepts that will be introduced in Section IV.

IV. MVP EXTENSION CONCEPTS

In this section the behavior rule extensions to the MVP algorithm are presented. The first concept is based on aircraft's relative positions and the four other concepts are based on their absolute positions. The area avoidance method is introduced and the steering rule hierarchy that integrates the different rule categories is presented last.

A. Relative position-based separation method

When studying Maas' swarming concept it was noted that the Flock Centering behavior caused aircraft to maneuver into conflicts and losses of separation. A new separation method is created based on this observation. This Velocity Averaging (VELAVG) method does not perform a flock-centering action and uses different weights for the two remaining steering actions. The swarming criteria are redefined such that an aircraft is only included in the ownship's swarm if the following statements are true:

- The horizontal distance is more than 10 and less than 15 nautical miles
- The heading difference is less than 90 degrees
- Both aircraft are inside the swarming area

The prescribed velocity vector $\mathbf{V}_{VELAVG}$ is calculated by taking a weighted average of the collision avoidance vector $\mathbf{V}_{CA}$ and the velocity averaging vector $\mathbf{V}_{VA}$ as given in Eq. 5:

$$\mathbf{V}_{VELAVG} = \frac{20 \cdot \mathbf{V}_{CA} + 1 \cdot \mathbf{V}_{VA}}{20 + 1} \quad (5)$$

The velocity averaging method is only used for aircraft that are inside the swarming area shown in Fig. 6. It extends from 80 nautical miles from the experiment center to the end of the corridor. For conflicting aircraft outside of this area and for conflicting aircraft that do not meet the three criteria the MVP method is applied.

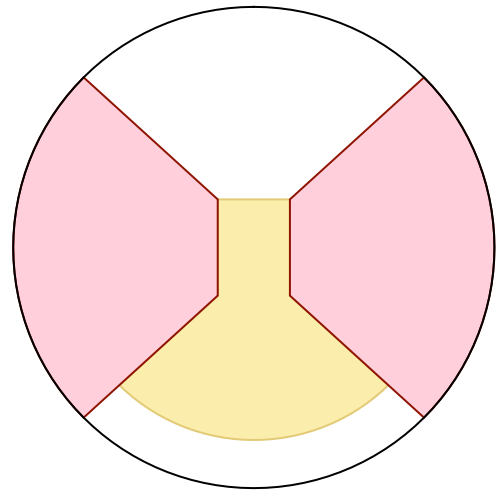


Fig. 6. Geometry for the VELAVG concept with the swarming area in yellow.

B. Absolute position-based separation methods

Four separation methods using the geovectoring concept are presented. From the first to the last method the geovectoring areas become more fine grained as the area sizes decrease. All geovectors are time-invariant and the areas do not overlap with the airspace restrictions.

The aim of all geovector methods presented here is to reduce the relative velocities between aircraft in the convergence and corridor areas and to allow aircraft to accelerate at the end of the corridor area and in the divergence area.

1) *Geovectoring Speed Concept (GV-SPD)*: The first geovectoring concept uses two geographic areas shown in Fig. 7. Area 1 extends 80 nautical miles outward from the center point and covers most of the corridor. Area 2 extends 45 nautical miles outward from the center point and covers the remaining part of the corridor.

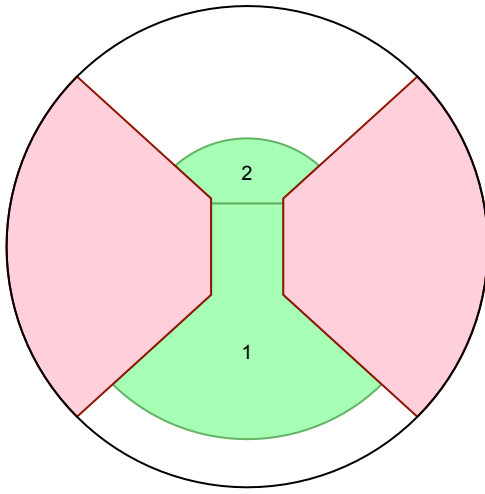


Fig. 7. Geometry for the GV-SPD concept with the geovectoring areas in green.

The velocity vector restrictions are given in Table I: in each area all traffic flies at the same speed and there are no restrictions on their courses.

TABLE I
GEOVECTOR RESTRICTIONS FOR THE GV-SPD CONCEPT.

Area	Speed restriction	Course restriction
1	458 knots GS	n.a.
2	473 knots GS	n.a.

2) *Geovectoring Zones Concept (GV-ZONES)*: The second geovectoring concept uses three geographic areas as shown in Fig. 8. Area 1 extends 80 nautical miles from the center point to the start of the corridor. Area 2 covers most of the corridor itself, and area 3 covers the remainder of the corridor and extends up to 45 nautical miles from the center point.

The velocity vector restrictions are given in Table II. In each area all traffic flies at the same speed and there are no course restrictions.

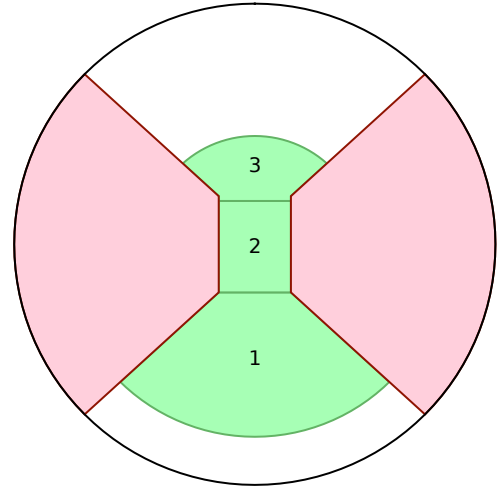


Fig. 8. Geometry for the GV-ZONES concept with the geovectoring areas in green.

TABLE II
GEOVECTOR RESTRICTIONS FOR THE GV-ZONES CONCEPT.

Area	Speed restriction	Course restriction
1	464 knots GS	n.a.
2	464 knots GS	[355, 5] deg
3	473 knots GS	n.a.

3) *Geovectoring Rings Concept (GV-RINGS)*: The third geovectoring concept uses multiple concentric rings around a central corridor area as shown in Fig. 9. Areas 1 and 7 extend from 80 to 60 nautical miles from the center point. Areas 2 and 6 cover the 60 to 40 nautical miles range and areas 3 and 5 extend from 40 nautical miles to the corridor. Area 4 covers the corridor itself.

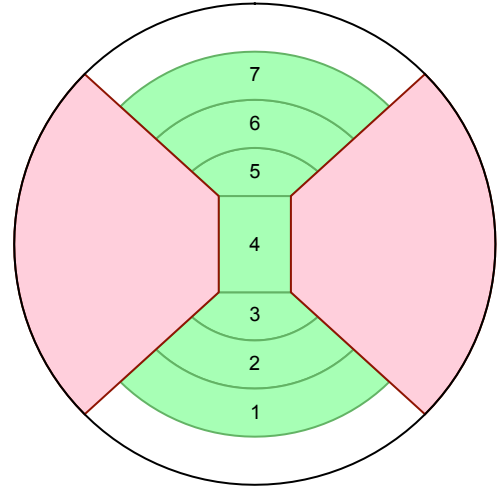


Fig. 9. Geometry for the GV-RINGS concept with the geovectoring areas in green.

The velocity vector restrictions are given in Table III. In the ring areas there is no course restriction but the allowable

speed range decreases the closer the ring is to the corridor. In the corridor area all aircraft fly at the same speed and the course is limited to a 10 degree range.

TABLE III
GEOVECTOR RESTRICTIONS FOR THE GV-RINGS CONCEPT.

Area	Speed restriction	Course restriction
1, 7	[453, 475] knots GS	n.a.
2, 6	[456, 472] knots GS	n.a.
3, 5	[459, 469] knots GS	n.a.
4	464 knots GS	[355, 5] deg

4) *Geovectoring Grid Concept (GV-GRID)*: The fourth and last geovectoring concept is the most complex and can be seen in Fig. 10. It combines geovector elements seen in the GV-ZONES and GV-RINGS methods with additional heading restrictions in the convergence zone.

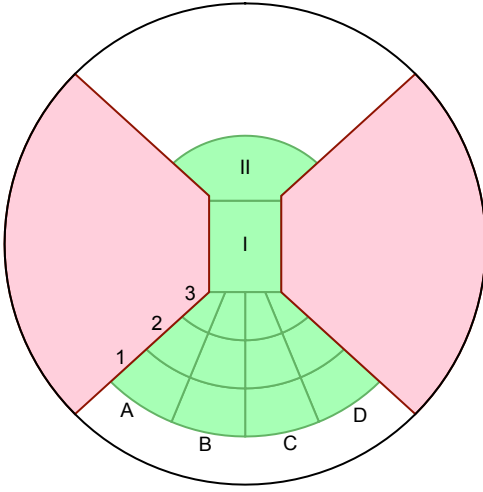


Fig. 10. Geometry for the GV-GRID concept with the geovectoring areas in green.

The three concentric areas are the same as in GV-RINGS and the four radial areas split the area between the airspace restrictions into equal angles. The 12 areas in the grid resulting from the intersections of overlapping speed ring and heading wedge geovectors each have both a speed and course restriction. The velocity vector restrictions are given in Table IV.

TABLE IV
GEOVECTOR RESTRICTIONS FOR THE GV-GRID CONCEPT.

Area	Speed restriction	Course restriction
ring 1	[453, 475] knots GS	n.a.
ring 2	[456, 472] knots GS	n.a.
ring 3	[459, 469] knots GS	n.a.
wedge A	n.a.	[33, 35] deg
wedge B	n.a.	[11, 12] deg
wedge C	n.a.	[347, 349] deg
wedge D	n.a.	[325, 327] deg
I	464 knots GS	[355, 5] deg
II	475 knots GS	n.a.

C. Area Avoidance Method

The area avoidance method uses state extrapolation with a 120 second look-ahead time to detect conflicts with the restricted airspaces. Because of the relatively small distances that aircraft can fly in this time a flat-earth approximation is used. The steering action required to avoid entering the area is calculated using a collision cone approach based on the tangents from the aircraft to the area as shown in Fig. 11.

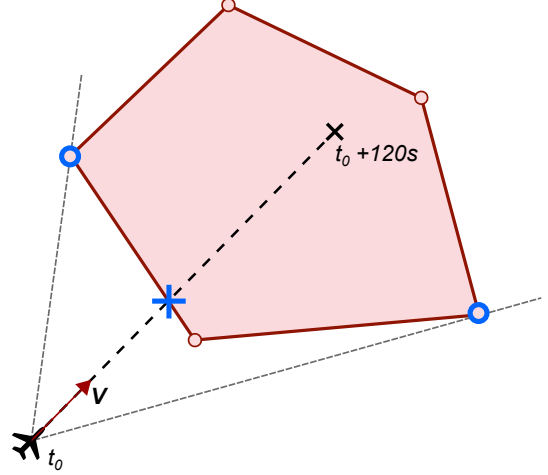


Fig. 11. Aircraft-area conflict detection with an arbitrary polygonal area. The aircraft state extrapolation and tangents to the area are shown.

The tangent closest to the active waypoint on the aircraft route is selected as the course for the resolution maneuver. The area avoidance method does not change the aircraft speed. Once the area avoidance method detects a conflict it remains active until the commanded resolution course is reached.

D. Steering Rule Hierarchy

To extend the MVP method with additional steering behaviors a steering rule hierarchy is used to define their order of precedence. The following three behavior type categories are distinguished:

- Area avoidance
- Traffic separation
- Route following

In this experiment only the behavior rules in the traffic separation category are varied. A schematic representation of the behavior hierarchy is shown in Fig. 12. The area avoidance behavior has the highest precedence, meaning that avoiding restricted airspaces is more important than solving aircraft-aircraft conflicts. In the baseline scenario the traffic separation behavior is implemented purely by the MVP method. In the absolute position based methods the MVP rules take precedence over the geovectoring rules, meaning that the geovector restrictions are ignored when a conflict occurs. For the relative position based method the pure MVP and velocity averaging rules have the same precedence but only one is active based on the criteria set in Section IV-A. Route following will only take place when neither the area avoidance or traffic separation rules prescribe a steering action for an aircraft.

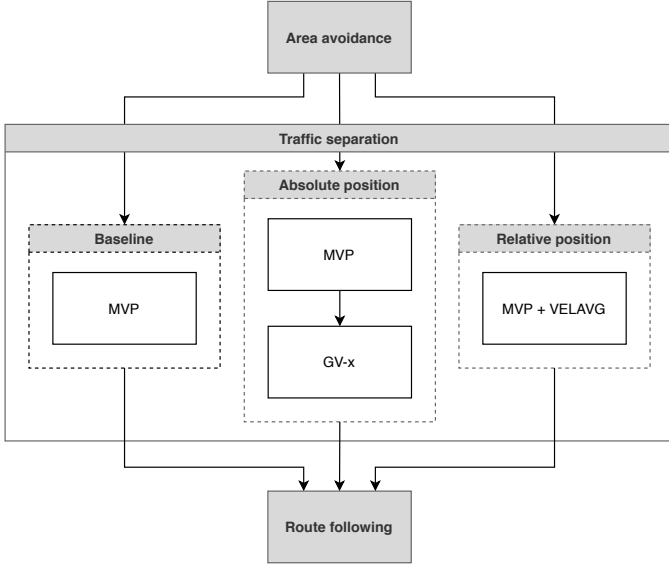


Fig. 12. Hierarchy of steering behaviors. ‘GV-x’ denotes each of the geovectoring methods.

V. EXPERIMENT DESIGN

This section introduces the setup used for the experiments in this paper. First the simulation environment is introduced, followed by the control, independent, and dependent variables. Finally, the experiment hypotheses are given.

A. Simulation environment

The environment used for the experimental simulations is the BlueSky ATM simulator that has been developed at Delft University of Technology [22]. The BlueSky project is open source and written in the Python programming language. It offers a fast-time simulation framework with various functionalities that can be extended to study ATM topics in a controlled environment. Simulations for this experiment are performed using a custom generated BlueSky scenario file for each experimental run. For the weather during all runs the standard atmosphere with zero wind is used.

For this experiment the behaviors given in the steering rule hierarchy from Section IV-D were implemented. For the area avoidance behavior a plugin was created to handle area conflict detection and resolution calculations. The traffic separation behavior types were implemented by extending the existing MVP, geovector, and swarming self-separation modules. For the route following behavior the existing BlueSky autopilot and Flight Management System modules were used with only minor adaptations.

B. Traffic Scenarios

The airspace geometry introduced in Section III is used throughout the entire experiment. All aircraft are created at a random point on the southern edge of the experiment area and follow a route via the two waypoints at the beginning and the end of the corridor. The destination waypoint is randomly placed on a 90 degree arc at 200 nautical miles from the experiment area center as shown in Fig. 13. Aircraft are

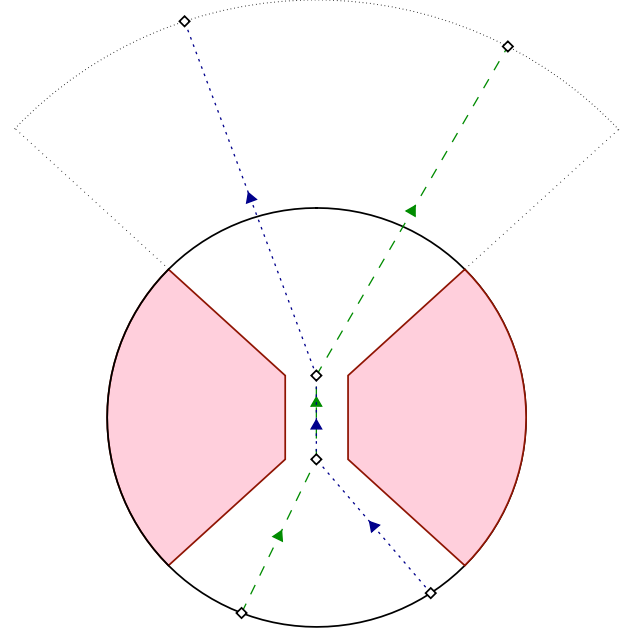


Fig. 13. Examples of two random aircraft routes and their associated waypoints.

automatically deleted from the simulation upon leaving the circular experiment area.

The rate at which aircraft spawn is determined by an average interval that is given by the traffic rate. Spawning locations are randomly chosen and a simple check is performed to minimize the chances that aircraft are in conflict at the moment they spawn. This is however not a hard guarantee since the actual traffic state at the time of spawning can not be predicted due to the ad hoc nature of maneuvers in self-separation concepts. In all scenarios aircraft spawn during a period of three hours. To discard any transient effects and study a steady state traffic density only those aircraft that spawn after the first 30 minutes and before the last 30 minutes are used.

To simulate a somewhat realistic traffic situation the experiments use a traffic mix that consists of four aircraft types as given in Table V. The average True Airspeed (TAS)

TABLE V
AIRCRAFT TYPES, AVERAGE SPEEDS AND PERCENTAGES OF TRAFFIC AS USED IN ALL EXPERIMENTS.

Type	Average TAS	Traffic percentage
A320	447 knots	25 %
B738	450 knots	25 %
A333	470 knots	25 %
B744	487 knots	25 %

for each aircraft type is given, and the speed of each specific instance of that type is randomly taken from a normal distribution with that average speed and a 9 knot standard deviation. Because this experiment takes place at a single altitude without any vertical maneuvering the main difference between these aircraft types are their allowable speed ranges. This influences their turning radii which affects the conflict resolution maneuvers.

C. Independent variables

In this experiment two independent variables are used. The research goal as stated in Section I is to investigate whether the performance of the MVP method in converging traffic flows can be improved by adding additional steering rules. For this reason the first independent variable is the separation method. The five concepts described in Section IV-D are compared to the baseline MVP method. For each scenario a run without any conflict resolution (denoted as ‘OFF’) is performed as well. These ‘OFF’ runs are only used in the calculation of some metrics as explained in the next section and will not be used directly. The second independent variable is the traffic level. Because the number of conflicts is related to the number of aircraft in an airspace the performance of these separation methods is compared across five traffic levels.

The resulting 7 by 5 experiment matrix is summarized in Table VI. For each of the 35 resulting experimental conditions 100 simulation runs are performed.

TABLE VI
EXPERIMENT MATRIX.

Variable	Levels	Values
Separation method	7	OFF, MVP, VELAVG, GV-SPD, GV-ZONES, GV-RINGS, GV-GRID
Traffic Levels	5	30, 60, 90, 120, 150 aircraft/hr

D. Dependent variables

The metrics by which the results of the experiment are evaluated are divided into four categories: safety, efficiency, stability and capacity. For each of these categories the dependent variables used in that category are described hereafter.

1) *Safety*: The safety metrics are used to judge a separation method’s ability to maintain a safe minimum distance between aircraft. In this experiment this minimum required separation is five nautical miles.

The number of conflicts n_{conf} is the measure of the number of situations in which a violation of the minimum separation distance is bound to happen and where the separation method must take action. A higher number of conflicts means that more of these potentially dangerous situations occur.

The number of losses of separation (LoS) n_{LoS} is the measure of the number of situations in which the minimum separation distance is actually violated. A higher number of losses of separation means that the separation method is unable to solve conflicts in a timely manner.

Not all conflicts turn into a LoS and a measure for the fraction of conflicts that are successfully resolved is given by the Intrusion Prevention Rate (IPR) [27]. The IPR definition is given by Eq. 6:

$$IPR = \frac{n_{conf} - n_{LoS}}{n_{conf}} \quad (6)$$

The IPR ranges from 0 to 1 where the former means that all conflicts turn into an LoS and the latter means that all conflicts are solved before they become a LoS.

Every LoS can be characterized by its severity LoS_{sev} . This is the measure that relates the distance at the closest point of approach during the intrusion d_{cpa} to the required minimum separation distance R_{min} as given in Eq. 7 [27]:

$$LoS_{sev} = \frac{R_{min} - d_{cpa}}{R_{min}} \quad (7)$$

The severity value ranges from 0 to 1 and the higher this value the smaller the distance the two aircraft during the event.

The total time in resolution t_{reso} is the measure for the amount of time during which aircraft are in conflict resolution maneuvers. Not all conflicts can be solved equally fast and this metric gives an indication of how much effort it takes to solve conflicts.

The number of area conflicts $n_{area,conf}$ is the measure for the number of situations in which the separation method maneuvers cause aircraft to be in conflict with the airspace restrictions. This means that within the look-ahead time of 120 seconds the aircraft is predicted to enter the airspace if no area avoidance action is taken.

The number of area intrusions $n_{area,int}$ is the number of situations in which the area avoidance method fails to prevent an aircraft from entering a restricted airspace. This number should ideally be zero because area avoidance is defined to be the most important element in the steering behavior hierarchy.

2) *Efficiency*: Conflict resolution maneuvers cause aircraft to deviate from their intended flight path routes. The fraction of extra travel distance d_{extra} gives a measure for the effect this has on the actual flight path. Its definition is given by Eq. 8:

$$d_{extra} = \frac{d_{total} - d_{route}}{d_{route}} \cdot 100\% \quad (8)$$

Here d_{total} is the actual total travel distance flown and d_{route} the flight plan route distance. Because aircraft are deleted from the simulations before reaching the final waypoint the actual total travel distance is calculated using the distance traveled up to the moment of deletion plus the distance remaining to the final waypoint.

3) *Stability*: The Domino Effect Parameter (DEP) is a metric that describes whether the use of a conflict resolution method reduces or increases the total number of conflicts. When the resolution maneuver to solve a conflict leads to one or more new conflicts this can be regarded as a “Domino Effect”. Resolution methods that increase the number of conflicts are said to destabilize the airspace. The DEP was first introduced by Bilimoria et al. but this research uses the adapted version defined by Sunil as given in Eq. 9 [27], [28]:

$$DEP = \frac{n_{conf}^{ON}}{n_{conf}^{OFF}} - 1 \quad (9)$$

In this equation n_{conf}^{OFF} is the number of conflicts without conflict resolution and n_{conf}^{ON} is the number of conflicts with activated conflict resolution. A higher DEP indicates a reduction in airspace stability when using a separation method.

4) *Capacity*: The previous metrics do not make any predictions and can only be used to describe a traffic situation as it is. The Capacity Assessment Method for Decentralized Air Traffic Control (CAMDA) is a method that can be used to estimate the maximum theoretical density of an airspace ρ_{max} using an semi-empirical model [29]. The CAMDA method is based on two assumptions: both the number of conflicts per unit distance traveled as well as the total aircraft count are approximately the same both in scenarios with and without conflict resolution.

The CAMDA model relates the maximum theoretical traffic density ρ_{max} to the actual traffic density ρ and the DEP as a function of the actual density via Eq. 10:

$$DEP(\rho) = \frac{\rho}{\rho_{max} - \rho} \quad (10)$$

The value of ρ_{max} can be estimated by fitting the equation above to a series of DEP measurements at different traffic densities. The CAMDA method is still new and relatively untested, especially in constrained airspaces. Therefore it is important that its assumptions are verified when evaluating the model's maximum traffic density estimate.

The dependent variables are briefly summarized in Table VII.

TABLE VII
SUMMARY OF DEPENDENT VARIABLES.

Type	Variable	Description
Safety	n_{conf}	Number of aircraft-aircraft conflicts
	n_{LoS}	Number of losses of separation
	LoS_{sev}	Loss of separation severity
	IPR	Intrusion prevention rate
	t_{reso}	Time in resolution
Efficiency	$n_{area,conf}$	Number of aircraft-area conflicts
	$n_{area,int}$	Number of area intrusions
	d_{extra}	Extra travel distance
	DEP	Domino Effect Parameter
	ρ_{max}	Maximum theoretical traffic density
Stability		
Capacity		

E. Hypotheses

From previous research it is known that the conflict rate is positively correlated with both the average velocity and the allowable heading range [30]. Reducing the average velocity and heading range can be done by reducing the relative velocity between aircraft. Thus, the separation methods in the current research aim to reduce the number of conflicts and losses of separation by lowering this relative velocity.

The first hypothesis is that the relative position based VELAVG method will perform better with higher traffic density than with lower traffic densities whereas the geovectoring methods performance will decrease with increasing traffic density. The relative velocity reduction effect of the velocity averaging steering rule is expected to be more pronounced if an aircraft is surrounded by a larger number of other aircraft. Because the conflict resolution behavior takes precedence over the geovectoring behavior it is expected that a larger traffic density will result in more conflict resolution maneuvers overruling the geovector restrictions.

The second hypothesis is that the performance of the geovector concepts increases when the difference in restrictions between neighboring geovector areas decreases. Smaller changes in aircraft heading and speed when entering a new geovector area are expected to reduce the relative velocities between aircraft. Smaller geovector area sizes enable more granular control are thus expected to have a larger effect.

VI. RESULTS

In this section the results of the 3500 experimental simulation runs are presented. For each metric the average value or the total count of occurrences is calculated per scenario run and the distribution of these values for the 100 runs per condition is presented in the form of box-and-whisker plots. The box shows the first and third quartile with the median in between and the whiskers show the data within 1.5 times the interquartile range from the median on each respective side. Outliers as well as values for the 'OFF' condition are only included in the figures when relevant.

Visual comparison between the five tested concepts and the baseline MVP method shows that for all metrics there is either a clear difference or very little difference at all. For this reason it was decided that there would be little added value in performing statistical tests on the results. All analysis in this section as well as the discussion in the next section is thus based on visual inspection of the presented figures.

A. Safety

The number of aircraft conflicts and losses of separation are given in Figures 14 and 15.

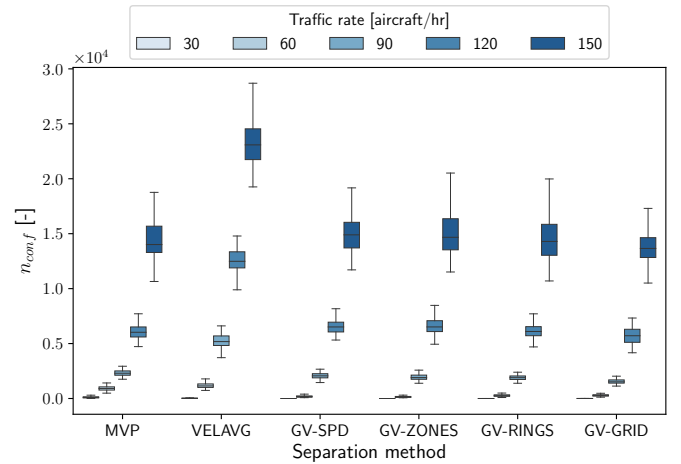


Fig. 14. Effect of traffic rate on the number of aircraft-aircraft conflicts for different separation method concepts.

It can be seen that for all separation methods the number of conflicts increases with increasing traffic rate. All four geovectoring methods have a slightly lower conflict count than the MVP method at the 30 and 60 aircraft/hr settings and no difference for the other rates. For the VELAVG method a higher number of conflicts at all traffic rates is seen compared to both the MVP baseline as well as all other methods. This can be explained by the fact that the VELAVG method does

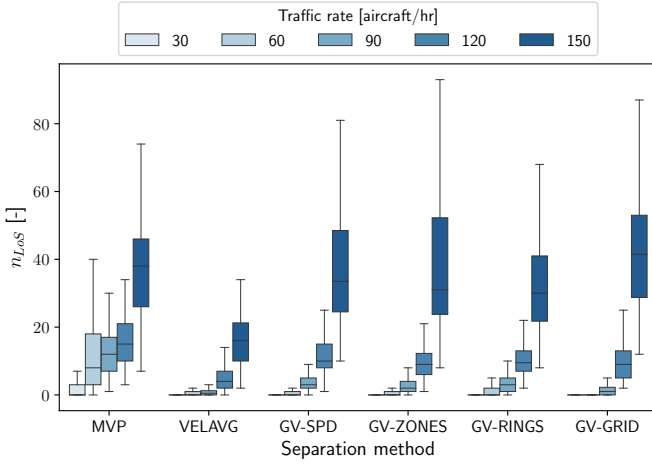


Fig. 15. Effect of traffic rate on the number of losses of separation for different separation method concepts.

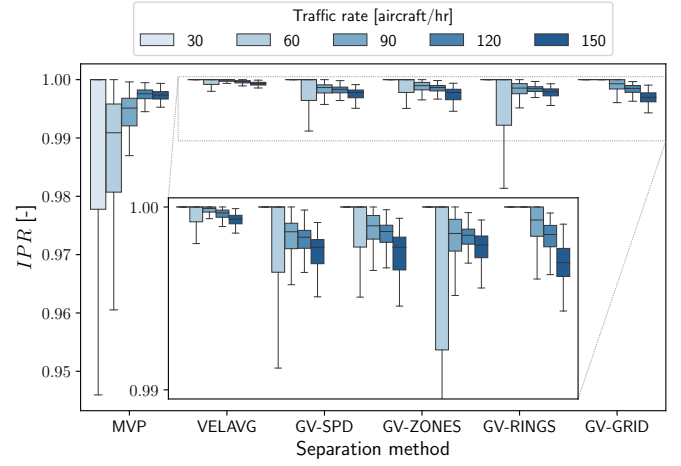


Fig. 17. Effect of traffic rate on the intrusion prevention rate for different separation method concepts.

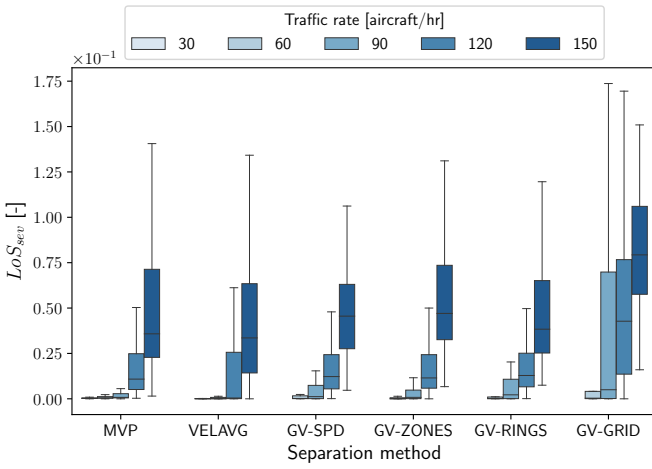


Fig. 16. Effect of traffic rate on the loss of separation severity for different separation method concepts.

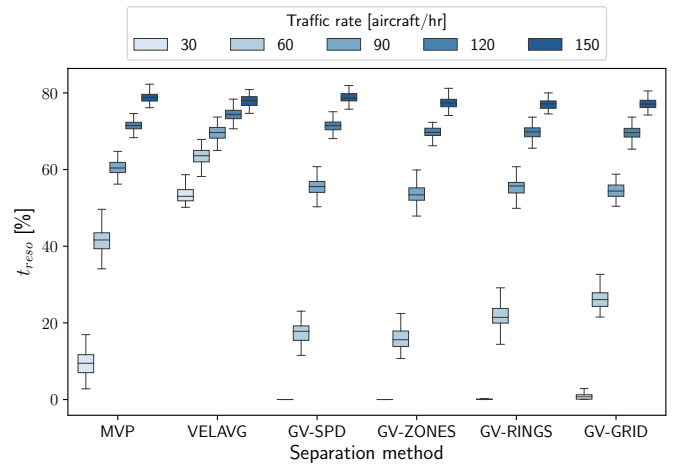


Fig. 18. Effect of traffic rate on the time in resolution for different separation method concepts.

not attempt to solve all conflicts but uses its swarming criteria and velocity averaging rule instead.

The number of losses of separation observed when using the VELAVG method is much lower than for the MVP baseline at all traffic rates. This is noteworthy given the worse performance of this method on the number of conflicts metric. Just as with this previous metric all geovectored methods perform better than the MVP method on this metric at the lower traffic rates but not at the higher ones. The severity of the losses of separation that did occur is shown in Fig. 16.

The vast majority of all loss of separation occurrences have a severity less than 0.1, which leaves 4.5 nautical miles of separation. All methods follow the same trend as the MVP baseline with the exception of the GV-GRID method. This last method causes intrusions that are much more severe at the 90 and 120 aircraft/hr levels and that are somewhat more severe at the 150 aircraft/hr level.

The Intrusion Prevention Rate (IPR) is shown in Fig. 17. All methods are very successful at preventing conflicts from turning into losses of separation. However, the MVP baseline

performs worse than the new methods at the lowest three traffic rates but similar at the highest two. The IPR values for the VELAVG method are consistently high at all traffic levels and this method can thus be regarded as the most effective at preventing conflicts turning into losses of separation.

The percentage of time aircraft spend in resolution can be seen in Fig. 18. There is a clear trend for all methods that a higher traffic rate with more conflicts also means that more time is spend in conflict resolution. This time spend in resolution increases asymptotically which can be explained by a higher number of multi aircraft conflicts at higher traffic rates. The geovectored methods have a lower time in conflict compared to the MVP method at the 30 and 60 aircraft/hr settings but perform similarly at the higher rates. The VELAVG method is a clear outlier at all but the highest traffic rate. This is because the velocity averaging steering behavior is active when aircraft are in swarming range even when they are not in conflict.

The number of aircraft-area conflicts and intrusions are shown in Figures 19 and 20. The number of aircraft-area

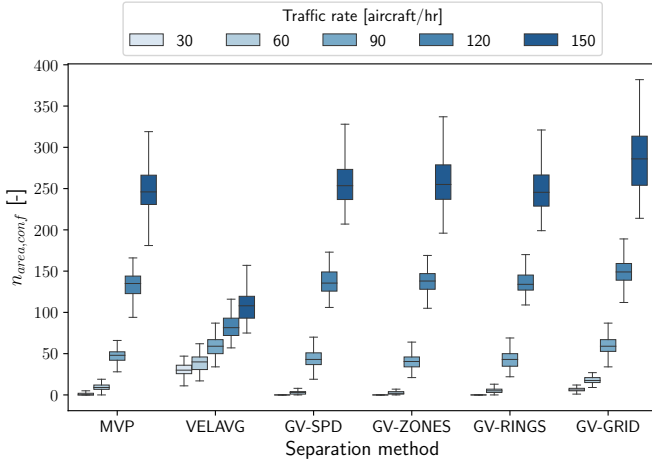


Fig. 19. Effect of traffic rate on the number of aircraft-area conflicts for different separation method concepts.

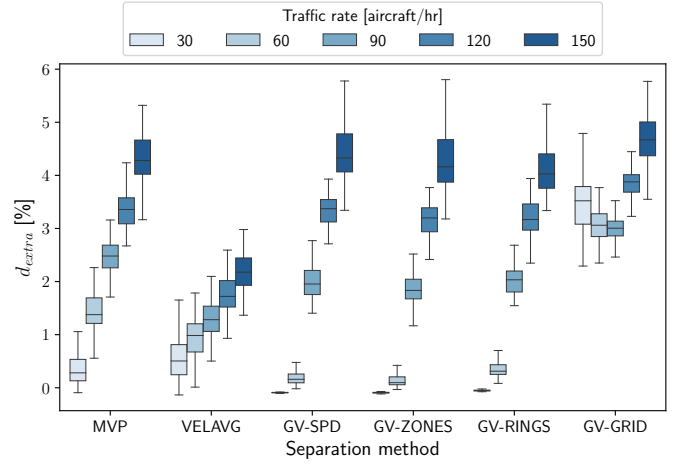


Fig. 21. Effect of traffic rate on the extra distance traveled for different separation method concepts.

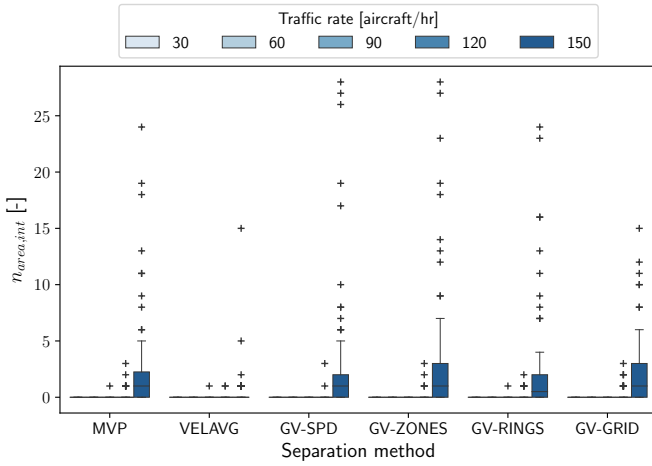


Fig. 20. Effect of traffic rate on the number of area intrusions for different separation method concepts.

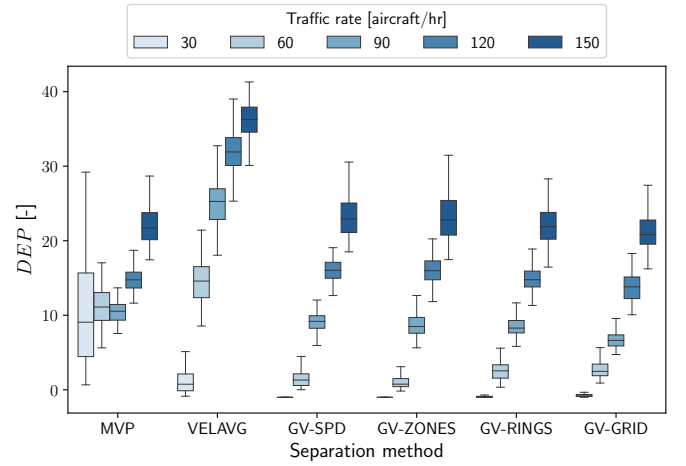


Fig. 22. Effect of traffic rate on the domino effect parameter for different separation method concepts.

conflicts shows an increase with traffic rate for all separation methods. The only outlier is the VELAVG method, which has more conflicts at the lower traffic rates but fewer at the higher settings. For all methods only a relatively small number of area intrusions occurs and mostly at the highest traffic level. The VELAVG method performs a bit better than the other methods at this level since all intrusions that occur are outliers. However the fact that intrusions do happen at all means that the current area avoidance method is not sufficient since its goal is to prevent them altogether.

B. Efficiency

The extra distance traveled with respect to the planned route is shown in Fig. 21. Three things can be noticed in this figure: Firstly, the rate at which the extra distance increases with the amount of traffic for the VELAVG method is approximately halved compared to the other methods. Consequently the VELAVG method outperforms at the highest traffic settings. Secondly, the GV-GRID method performs worse than any of the other methods at the lowest traffic levels. This can

be explained by the effect of the heading restrictions in the convergence zone which can be overruled by the conflict resolution behavior. Finally, the GV-SPD, GV-ZONES, and GV-RINGS methods all outperform the other methods at the lowest two traffic levels but have no noticeable effect at higher settings.

C. Stability

The Domino Effect Parameter (DEP) results are shown in Fig. 22. It can be seen that all separation methods have a large destabilizing effect ($DEP \gg 0$) on the number of conflicts and result in much more occurrences than when not using conflict resolution. All four geovectoring methods have a comparable effect on stability and outperform the MVP method at the lowest traffic rates but have similar results at the higher settings. Only the geovectoring methods at the 30 aircraft/hr setting consistently result in DEP values lower than zero indicating a stabilizing effect. The VELAVG method also performs better at the lowest traffic rate, but far worse at the higher rates when compared to the MVP method.

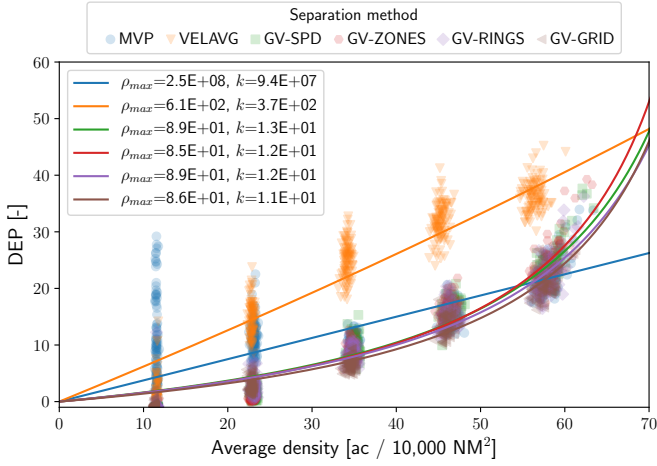


Fig. 23. Curve fits and parameter estimates for the adapted CAMDA model using experimental data.

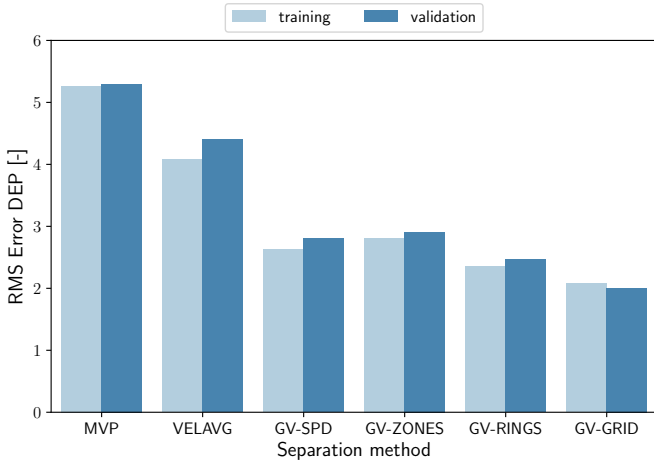


Fig. 24. Root mean square errors of training and validation sets for the adapted CAMDA model fitting.

D. Capacity

The CAMDA model as discussed in Section V-D4 could not be fitted to the simulation data with linear nor nonlinear regression. A model parameter k was therefore introduced resulting in the adapted model given by Eq. 11. This parameter also corrects for differences in scenario characteristics between this experiment and the assumed scenario for which the CAMDA model was derived.

$$DEP(\rho) = k \cdot \frac{\rho}{\rho_{max} - \rho} \quad (11)$$

The experiment data was randomly divided into a training and a validation set respectively containing 60% and 40% of the data. The model was fitted to the training data set using nonlinear regression with these two parameters. The resulting curve fits and values for ρ_{max} and k are shown in Fig. 23.

It can be seen that there is a large variation in parameters between curves for the different separation methods. The geovectoring methods result in similar curves with comparable parameter values, albeit with k values of approximately 12. The MVP and VELAVG methods seem to result in almost

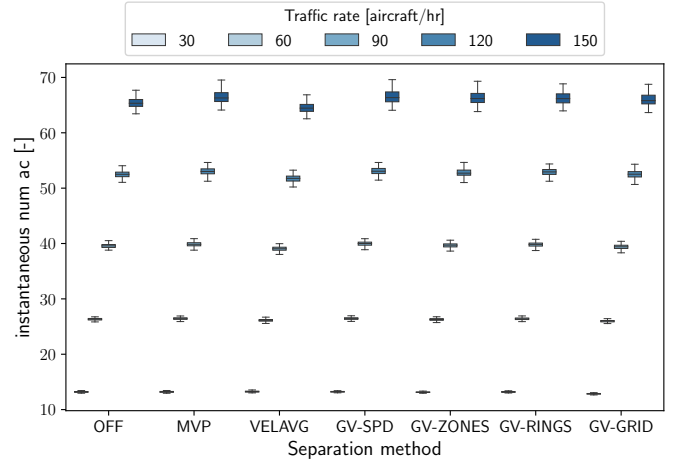


Fig. 25. Effect of traffic rate on the average instantaneous number of aircraft in the simulation for different separation method concepts.

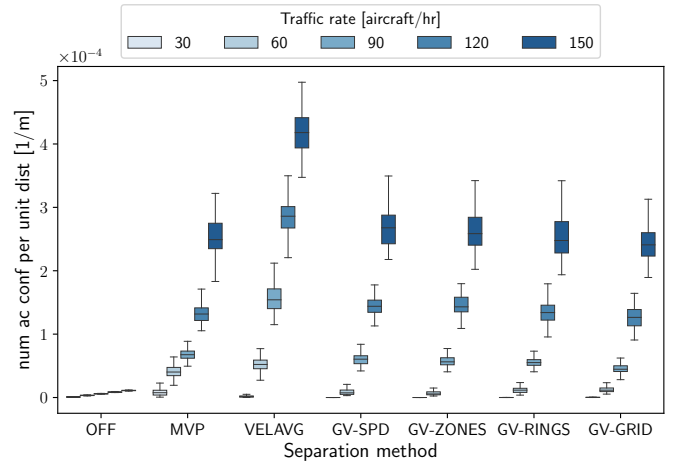


Fig. 26. Effect of traffic rate on the number of conflicts per unit distance flow for different separation method concepts.

linear curves with very high values for both ρ_{max} and k . A comparison between the root mean square values of the models with respect to both data sets is shown in Fig. 24.

The root mean square error values are approximately equal for both data sets, indicating that the curves are not over-fit to the training set. As stated before in Section V-D4 the CAMDA model makes the assumptions that both the instantaneous number of aircraft as well as the number of conflicts per unit distance flow is approximately the same both in situations with and without conflict resolution. To validate these assumptions the values of these metrics are shown in Figures 25 and 26.

From these two figures it becomes apparent that the instantaneous number of aircraft is almost constant between the 'OFF' case and all separation methods. The average number of conflicts per unit distance flow however is much higher for all separation methods compared to the 'OFF' case. Assumption one of the CAMDA model thus holds for all separation methods and assumption two is violated, albeit to almost the same degree for all separation methods and slightly worse for the VELAVG method. This follows from the faster

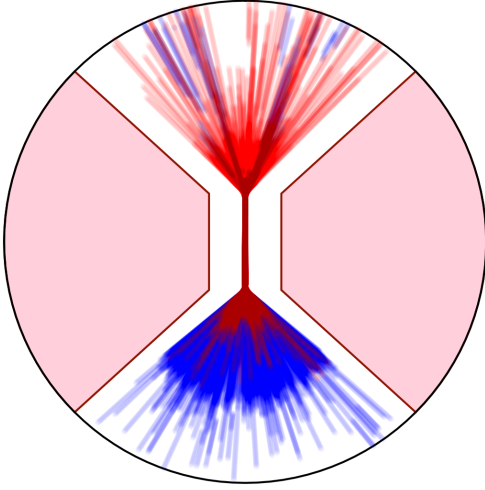


Fig. 27. Locations of traffic conflicts (blue) and losses of separation (red) without conflict resolution at traffic rate 90 aircraft/hr.

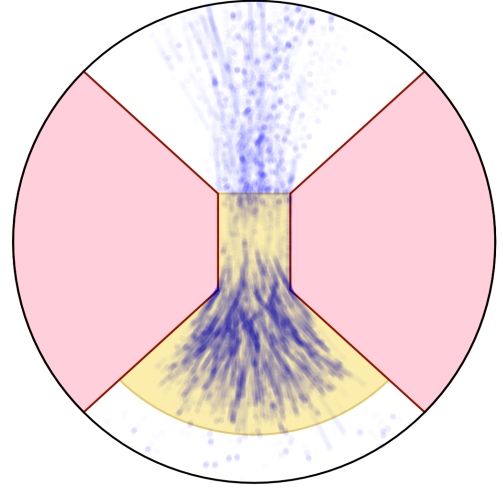


Fig. 29. Locations of traffic conflicts (blue) and losses of separation (red) using the VELAVG method at traffic rate 90 aircraft/hr.

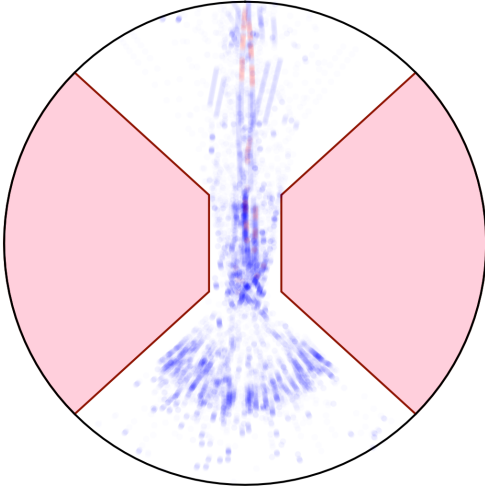


Fig. 28. Locations of traffic conflicts (blue) and losses of separation (red) using the MVP method at traffic rate 90 aircraft/hr.

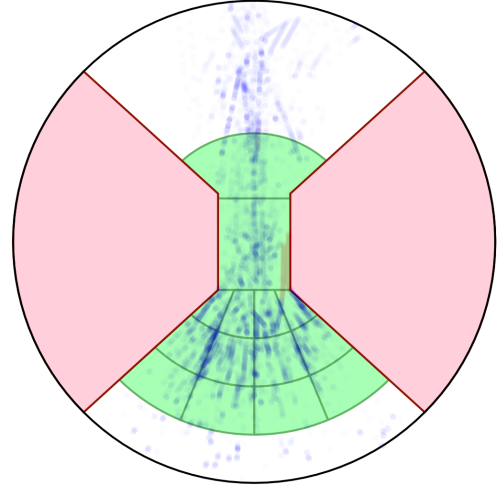


Fig. 30. Locations of traffic conflicts (blue) and losses of separation (red) using the GV-GRID method at traffic rate 90 aircraft/hr.

increase in number of conflicts with traffic rate for this method while the extra distance traveled when using it grows at a lower rate than the other methods (see Figures 14 and 21).

VII. DISCUSSION

The goal of this research was to investigate the feasibility of extending the MVP method with additional steering behaviors for use in converging traffic flows. The results of the experimental simulations show that in some situations the relative position-based VELAVG method performs better than the MVP method, whereas in other settings the four absolute position-based geovectoring methods perform better. This section evaluates the performance of the five tested methods and offers some suggestions for further research.

A. Evaluation of hypotheses

1) *Hypothesis 1:* The first hypothesis posed in Section IV was that the VELAVG method would have better performance at higher traffic rates whereas the geovectoring methods were expected to perform better at lower rates. Most notable from the results presented in the previous section is that the VELAVG method resulted in more conflicts yet it had fewer losses of separation (Figures 14 & 15). The severity of the losses of separation that did occur were comparable to the baseline MVP method except for the GV-GRID method which This can be explained by the fact that the conflicts that do occur using this method are more spread out through the convergence zone up to the beginning of the corridor which leaves more room to maneuver and thus can reduce the number of losses of separation.

Figures 27-30 show the locations at which an aircraft was

in either a conflict or a loss of separation with different conflict resolution methods. Each dot represents one aircraft and the positions are logged at a one-second interval. The same two randomly chosen traffic scenarios are shown using four different traffic separation methods to highlight the differences in traffic flow.

Some notable differences can be seen in these figures. For conflict resolution "OFF" it can be seen that the aircraft follow the planned route and almost all conflicts become losses of separations. The MVP method shows a different situation: initially most conflicts happen halfway through the convergence zone and are then resolved before a second hot spot of conflicts exists within the corridor. At the end of the corridor there are several sets of close-to-parallel conflict 'tracks', these are caused by aircraft that are supposed to cross paths but instead end up pushing each other away from their respective destinations. Of the geovectoring methods only the situation using the GV-GRID method is shown. The other GV methods have conflict location patterns very similar to the MVP baseline situation and can be found in Appendix A. The GV-GRID method shows a clustering of conflict locations near the radial edges of the geovector areas. This could be explained by the fact that the course restrictions cause aircraft in different radial sections to fly paths that may converge before the entrance of the corridor, depending on where the aircraft enter the course restriction. An more complete overview of conflict locations across all methods and across all traffic levels is shown in Appendix A.

To summarize: the VELAVG method reduces airspace stability and safety by increasing the conflict rate and domino effect parameter at higher traffic rates. The GV-SPD, GV-ZONES, and GV-RINGS methods perform better than the MVP method on all metrics at lower traffic rates and comparable at higher rates. The GV-GRID method performs similar to the other three geovectoring methods but has lower efficiency and worse intrusion severities even at lower traffic rates. The first hypothesis is thus partially correct.

2) *Hypothesis 2*: The second hypothesis was that the geovectoring methods would perform better when the geovector restrictions are applied with a higher granularity. Based on the conflict rate model it was expected that gradual changes in restrictions between different areas would reduce the relative velocities and heading differences between aircraft leading to fewer conflicts and losses of separation [30]. However for almost all metrics there is very little difference between each of the geovectoring methods. Only the GV-GRID method performs worse on the extra travel distance metric and the loss of separation severity metric, both at the lower traffic settings. Even on these metrics its performance is similar to the other geovectoring methods at the highest three rates. This can be explained by the fact that the GV-GRID method is the only geovectoring method that restricts aircraft's courses in the convergence zone. The presence of these course restrictions thus seems to have the opposite effect as intended. Since the main differences between the four geovectoring methods are the size of the individual geovector areas and ranges of allowable courses and speeds the second hypothesis is rejected.

B. Further observations

Because the combination of self-separation using the MVP method together with airspace restrictions has not been studied much before some more general observations are given here.

In Figures 29-30 it can be seen that conflicts and losses of separation do not only occur in the convergence zone and the corridor but also in the divergence zone as well. The conflicts here have two main causes: faster aircraft overtaking slower aircraft and aircraft whose flight paths towards their destination waypoints cross each other after exiting the corridor. These situations often lead to shallow-angle conflicts (seen as parallel lines of conflict locations in the figures) where both aircraft are unable to fly towards their destination and repeatedly turn in and out of conflict.

None of the methods are successful at preventing airspace intrusions completely and the differences in performance on this metric between methods is limited since they all use the same area avoidance rule. Due to the emergent behavior of these decentralized methods in some situations area conflicts occur with such angles that the currently used shortest-turn to avoid airspaces is not sufficient. Because of aircraft minimum turn radii these area conflict resolutions sometimes actively steer aircraft into a restricted airspace.

Fitting the CAMDA model to the results from this experiment requires the introduction of a model parameter as described in Section VI-D. The underlying reason is that the CAMDA model assumes a traffic situation that is uniformly distributed in all directions whereas in this experiment there is a unidirectional traffic flow in a limited heading range and the model parameter is required to account for the differences. In Fig. 23 it can be seen that the variation in both k and ρ_{max} is several orders of magnitude which makes it difficult to compare the different methods with each other. Only for the four geovectoring methods can it be concluded that their effect on airspace capacity is similar. The VELAVG method seems to result in an almost linear curve, which can be explained by the fact that especially in the narrowest part of the airspace the differences in speed and course between aircraft is minimal and the traffic flow becomes almost one dimensional. For the MVP method no conclusions are drawn because the spread in DEP values at low traffic rates is very large and the curve seems to be skewed towards these values.

C. Recommendations

The VELAVG method showed a DEP growth trend that looks linear whereas the geovectoring methods show a clear trend of accelerating growth. However, the VELAVG method still results in more conflicts than the other methods at the traffic levels tested in this experiment. It is recommended to investigate whether it is possible to improve on the VELAVG results by lowering the number of conflicts while retaining this linear growth trend.

In the previous section the observation was made that none of the methods succeeded at preventing airspace intrusions. The effects that the different rules in the steering rule hierarchy have on each other are not fully understood yet. It is recommended to further study these interactions and include

other methods of area avoidance to find out if it is possible to guarantee zero airspace intrusions.

In the comparison between the baseline MVP method and the concepts that add geovectoring rules it becomes apparent that the performances differ most at lower traffic rates. The range of traffic rates studied in this experiment is quite large and it would be recommended to further study these methods at a narrower range of lower traffic intensities.

In the current experiment all aircraft fly at a single altitude which means that the vertical dimension is not available to resolve conflicts. Replacing this single altitude with unidirectional altitude blocks might increase the rate at which conflicts can be solved and intrusions prevented.

The separation method concepts adding geovectoring rules are defined using the airspace geometry chosen for this experiment. Further research should be performed to find out whether similar methods produce comparable results in different airspace geometries.

The dependent variables used in this experiment mostly give insight at macro level only. It is recommended to consider other types of metrics to improve understanding of conflicts and losses of separation at a more microscopic level.

The final recommendation is to perform statistical testing to improve understanding of the differences between the separation methods. While the general trends are clear and can be observed visually there are plenty of metrics where the differences in results between methods are small. It could be beneficial to use a statistics-based approach to better understand whether these differences are significant or not.

VIII. CONCLUSION

This paper investigated the use of the MVP self-separation method in a converging traffic flow between restricted airspaces by adding additional steering behaviors. A steering rule hierarchy consisting of area avoidance, traffic separation, and route-following steering behaviors was developed. Five different traffic separation methods were designed, one based on relative positions using a velocity averaging rule and four others based on absolute position using geovectoring rules. An experiment with fast-time simulations was conducted in which the MVP algorithm was extended with these additional steering rules. From this experiment the following conclusions were drawn:

- It is possible to extend the MVP algorithm with additional steering rules to enable its use in converging traffic scenarios. Further research into the interaction effects between the different rules in the steering behavior hierarchy is suggested.
- The combination of emergent behavior caused by many aircraft interactions using decentralized self-separation methods and the minimum turn radius of aircraft means that the simple collision cone approach for area avoidance used in this research does not guarantee zero intrusions of restricted airspaces.
- Although the VELAVG method increases the conflict rate it results in fewer losses of separation and has the lowest number of area conflicts and intrusions. It is

recommended to reevaluate whether the MVP strategy of solving a conflict as soon as it is detected can be improved upon using other sets of criteria similar to the VELAVG method.

- The GV-SPD, GV-ZONES, and GV-RINGS methods performed better than the baseline MVP method at low traffic rates and similarly at higher traffic rates. In the latter cases the geovector restrictions were ignored in favor of the MVP conflict resolution behavior which has a higher priority. The GV-GRID method using more granular geovectors performed worst of the geovectoring methods, in particular on safety and efficiency metrics.

REFERENCES

- [1] International Civil Aviation Organization, "Long-Term Traffic Forecasts Passenger and Cargo," Tech. Rep., 2018.
- [2] Federal Aviation Administration, "FAA Aerospace Forecast Fiscal Years 2020-2040," Federal Aviation Administration, Washington, DC, Tech. Rep., 2020.
- [3] SESAR Joint Undertaking, "European Drones Outlook Study," Tech. Rep. November, 2016.
- [4] Volpe National Transportation Systems Center, "Unmanned Aircraft System (UAS) Service Demand 2015-2035: Literature Review and Projections of Future Usage," Tech. Rep. September 2013, 2013.
- [5] C. Wargo, C. Snipes, A. Roy, and R. Kerczewski, "UAS industry growth: Forecasting impact on regional infrastructure, environment, and economy," in *2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC)*, vol. 2016-Decem. IEEE, sep 2016, pp. 1–5.
- [6] Commission of the European Communities, "State of progress with the project to implement the new generation European air traffic management system," Brussels, Belgium, 2007.
- [7] Federal Aviation Administration, "The Future of the NAS," Washington, DC, Tech. Rep., 2016.
- [8] S. Hah, B. Willems, and R. Phillips, "The effect of air traffic increase on controller workload," *Proceedings of the Human Factors and Ergonomics Society*, pp. 50–54, 2006.
- [9] A. Majumdar and J. Polak, "Estimating Capacity of Europe's Airspace Using a Simulation Model of Air Traffic Controller Workload," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1744, no. 1, pp. 30–43, jan 2001.
- [10] J. M. Hoekstra, R. C. J. Ruigrok, and R. N. H. W. Van Gent, "Free flight in a crowded airspace?" in *3rd USA/Europe Air Traffic Management Research and Development Seminar*, no. June, Naples, Italy, 2000.
- [11] M. Strohmeier, M. Schafer, V. Lenders, and I. Martinovic, "Realities and challenges of nextgen air traffic management: the case of ADS-B," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 111–118, may 2014.
- [12] J. Kuchar and L. Yang, "A review of conflict detection and resolution modeling methods," *IEEE Transactions on Intelligent Transportation Systems*, vol. 1, no. 4, pp. 179–189, 2000.
- [13] J. Hoekstra, R. van Gent, and R. Ruigrok, "Conceptual design of free flight with airborne separation assurance," in *Guidance, Navigation, and Control Conference and Exhibit*. Boston, Massachusetts: American Institute of Aeronautics and Astronautics, aug 1998, pp. 807–817.
- [14] M. S. Eby, "A Self-Organizational Approach for resolving Air Traffic Conflicts," *The Lincoln Laboratory Journal*, vol. 7, no. 2, pp. 239–253, 1994.
- [15] S. M. Green, "En route Spacing Tool : Efficient Conflict-free Spacing to Flow-Restricted Airspace," in *3rd USA/Europe Air Traffic Management Research and Development Seminar*, Naples, Italy, 2000.
- [16] N. Doble, R. Hoffman, P. Lee, J. Mercer, B. Gore, N. Smith, and K. Lee, "Current Airspace Configuration Practices and Their Implications for Future Airspace Concepts," in *The 26th Congress of ICAS and 8th AIAA ATIO*, no. September. Anchorage, Alaska: American Institute of Aeronautics and Astronautics, sep 2008, pp. 1–13.
- [17] J. M. Prete, "Aircraft routing in the presence of hazardous weather," PhD Thesis, Stony Brook University, 2007.
- [18] H. C. Christmann and E. Johnson, "Modeling Urban Environments for Communication-Aware UAV Swarm Path Planning," in *AIAA Modeling and Simulation Technologies Conference*, no. August. Toronto, Canada: American Institute of Aeronautics and Astronautics, aug 2010.
- [19] C. W. Reynolds, "Steering Behaviors For Autonomous Characters," *Game developers conference*, vol. 1999, pp. 763–782, dec 1999.

- [20] A. Kieskamp, "Reducing Complexity in Self-Separated Air Traffic by Alignment and Cohesion," Master Thesis, Delft University of Technology, 2009.
- [21] J. Maas, E. Sunil, J. Ellerbroek, and J. Hoekstra, "The Effect of Swarming on a Voltage Potential-Based Conflict Resolution Algorithm," in *7th International Conference on Research in Air Transportation (ICRAT 2016)*, Philadelphia, Pennsylvania, 2016.
- [22] J. M. Hoekstra and J. Ellerbroek, "BlueSky ATC Simulator Project: an Open Data and Open Source Approach," in *7th International Conference on Research in Air Transportation (ICRAT 2016)*, Philadelphia, Pennsylvania, 2016, pp. 1–8.
- [23] J. Ellerbroek, "Airborne Conflict Resolution in Three Dimensions," PhD thesis, Delft University of Technology, 2013.
- [24] J. Maas, "A Quantitative Comparison of Conflict Resolution Strategies for Free Flight," Master thesis, Delft University of Technology, 2015.
- [25] A. Chakravarthy and D. Ghose, "Obstacle avoidance in a dynamic environment: a collision cone approach," *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, vol. 28, no. 5, pp. 562–574, 1998.
- [26] J. M. Hoekstra, J. Ellerbroek, E. Sunil, and J. Maas, "Geovectoring : Reducing Traffic Complexity to Increase the Capacity of UAV airspace," in *8th International Conference on Research in Air Transportation (ICRAT 2018)*, Castelldefels, Spain, 2018.
- [27] E. Sunil, J. Ellerbroek, J. Hoekstra, A. Vidosavljevic, M. Arntzen, F. Bussink, and D. Nieuwenhuisen, "Analysis of Airspace Structure and Capacity for Decentralized Separation Using Fast-Time Simulations," *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 1, pp. 38–51, jan 2017.
- [28] K. Bilimoria, K. Sheth, H. Lee, and S. Grabbe, "Performance evaluation of airborne separation assurance for free flight," in *18th Applied Aerodynamics Conference*, no. August. Denver, Colorado: American Institute of Aeronautics and Astronautics, aug 2000.
- [29] E. Sunil, J. Ellerbroek, and J. M. Hoekstra, "CAMDA: Capacity Assessment Method for Decentralized Air Traffic Control," in *8th International Conference on Research in Air Transportation (ICRAT 2018)*, Castelldefels, Spain, 2018.
- [30] J. M. Hoekstra, J. Maas, M. Tra, and S. E., "How Do Layered Airspace Design Parameters Affect Airspace Capacity and Safety ?" in *7th International Conference on Research in Air Transportation (ICRAT 2016)*, Philadelphia, Pennsylvania, 2016.

Part II

Appendices

Appendix A

Conflict location figures

This appendix presents a number of figures showing the locations of aircraft conflicts and losses of separation, most of which were not included in the research paper. For every combination of separation method and traffic rate settings these locations are shown by combining the results of the same two randomly chosen scenarios. The figures are grouped by separation method to show the differences in location patterns between the tested traffic rates.

A-1 No conflict resolution

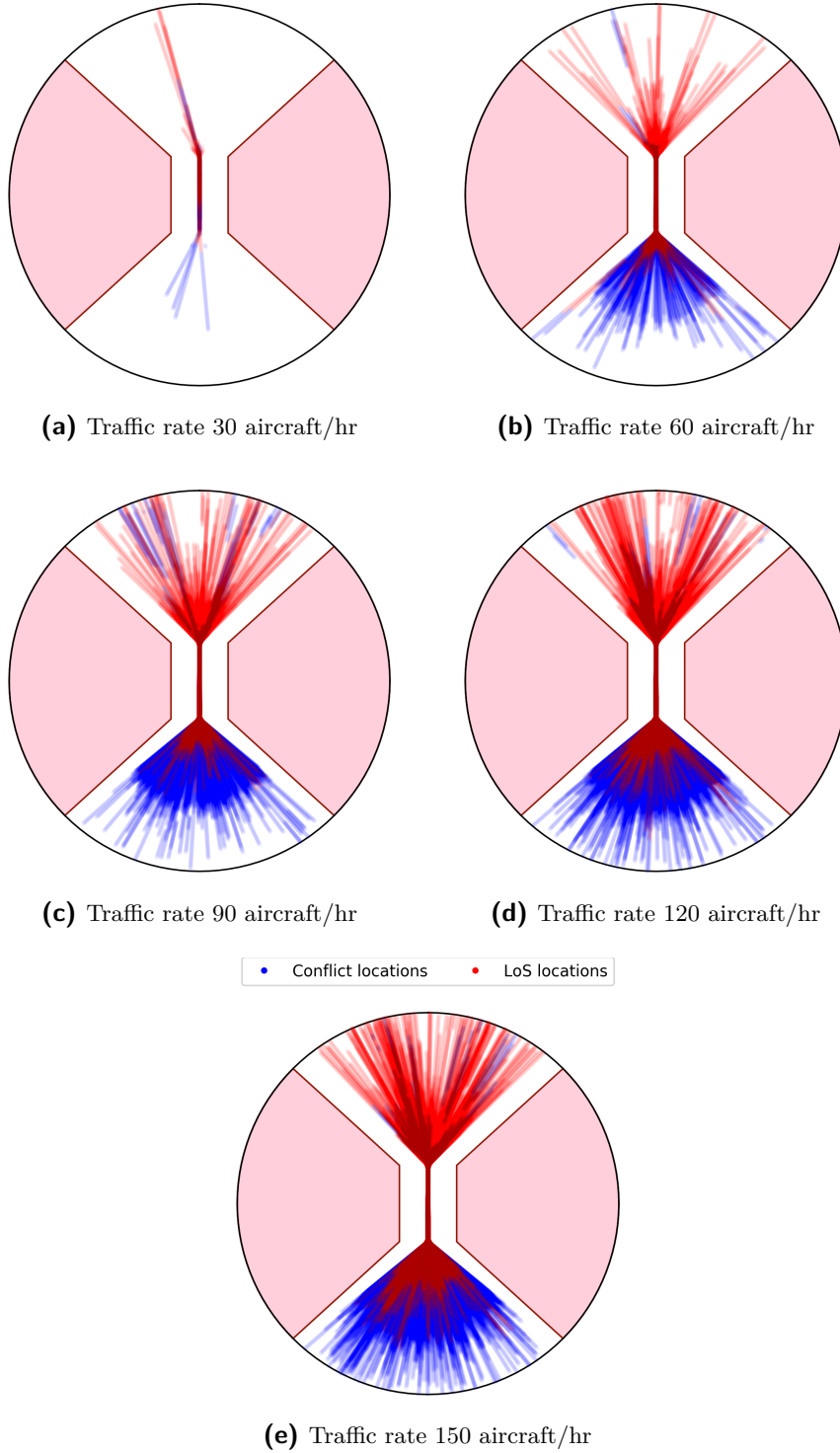


Figure A-1: Conflict and loss of separation locations without conflict resolution.

A-2 Modified Voltage Potential Method

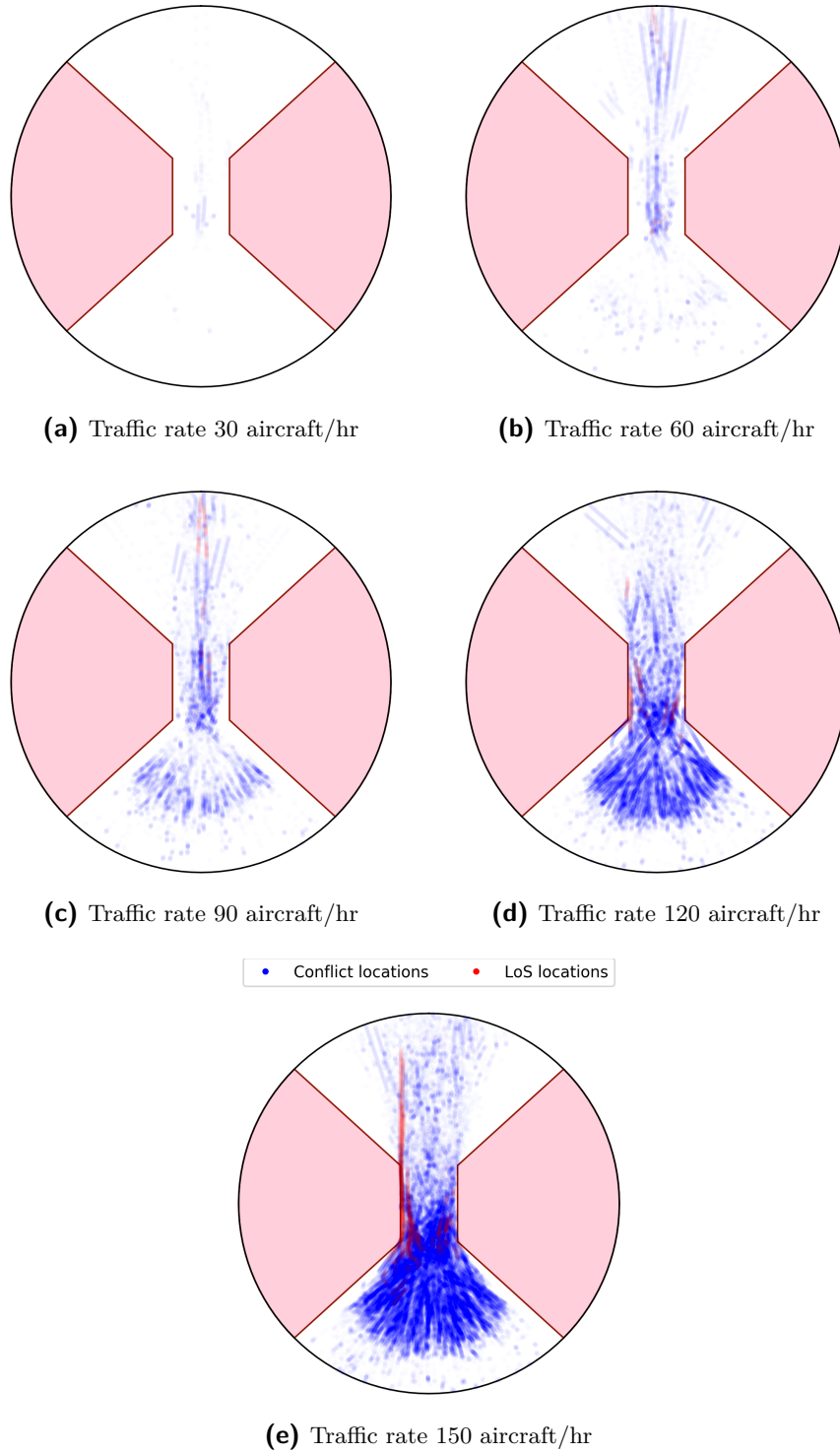


Figure A-2: MVP method conflict and loss of separation locations

A-3 Velocity Averaging Method

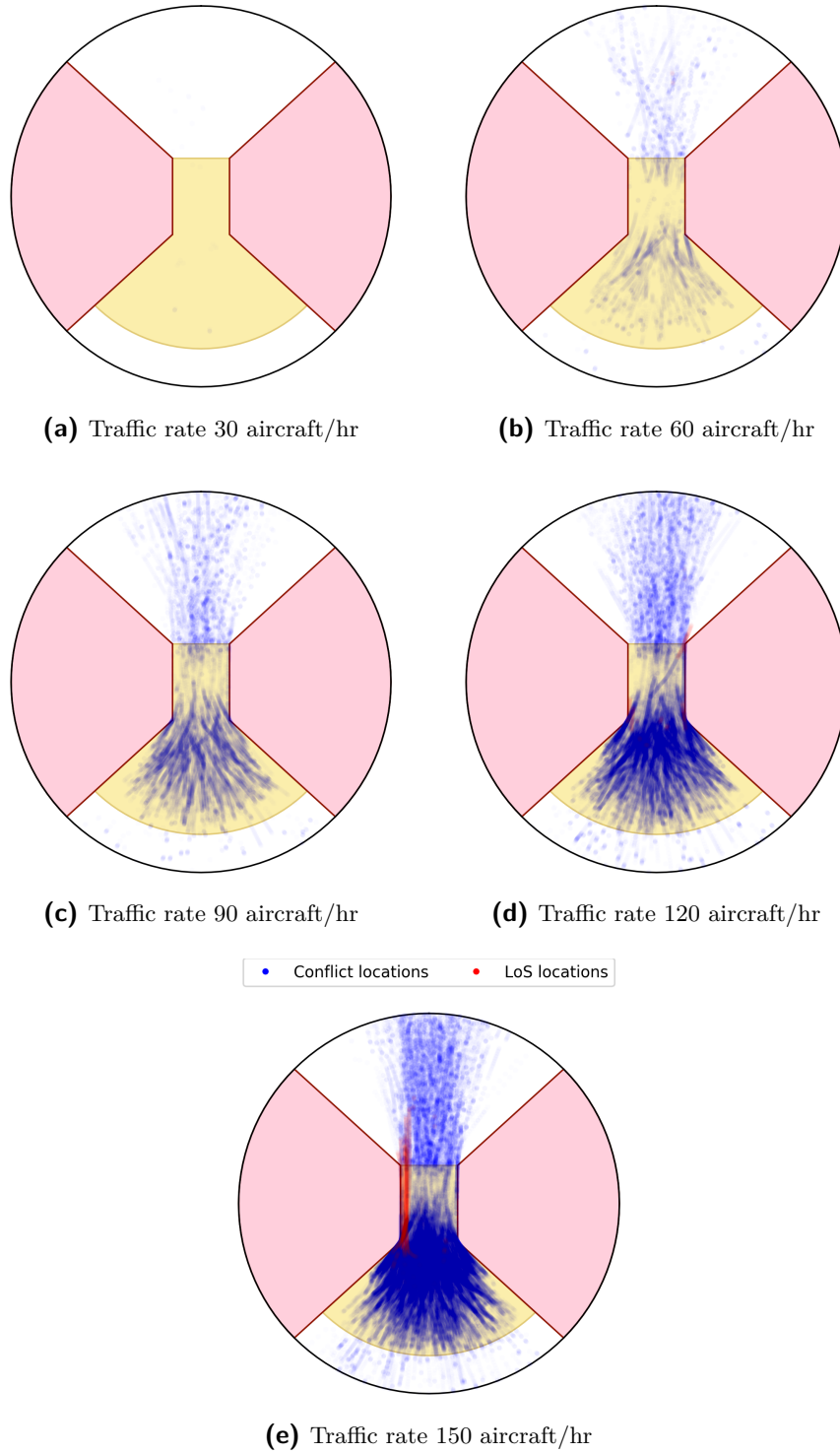


Figure A-3: Velocity averaging method conflict and loss of separation locations

A-4 GV-SPD Method

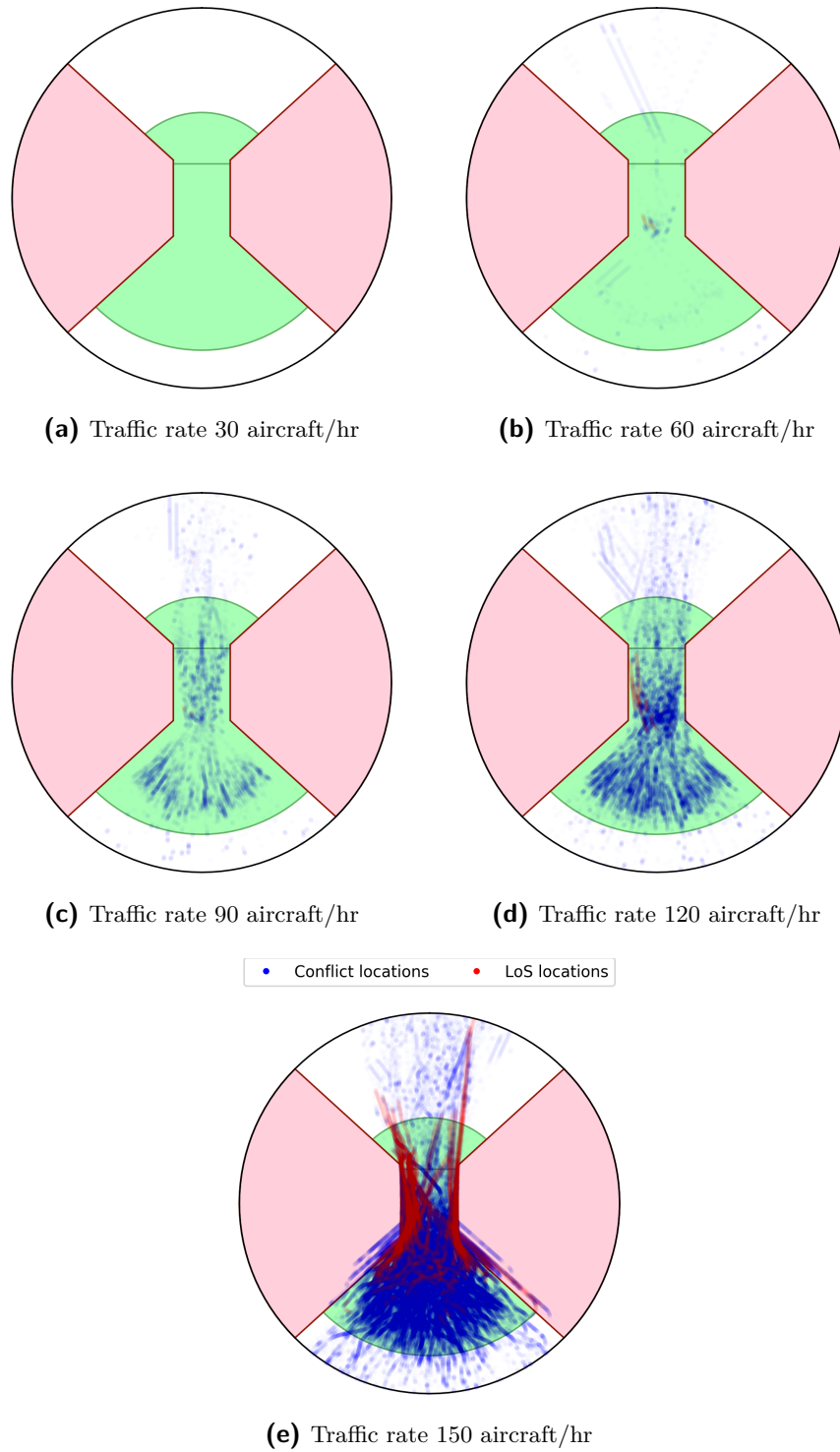


Figure A-4: Geovectoring method 1 conflict and loss of separation locations

A-5 GV-ZONES Method

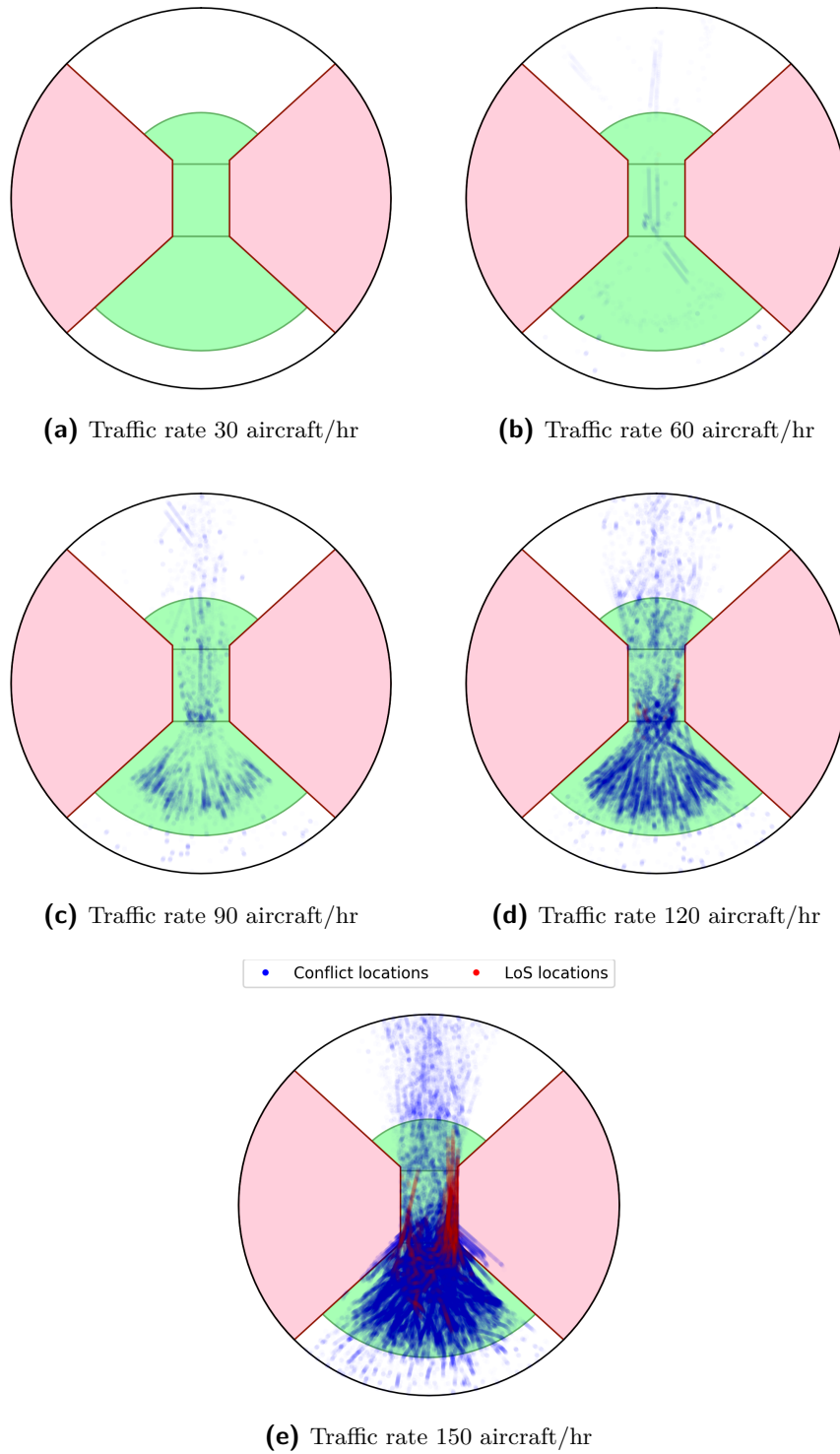


Figure A-5: Geovectoring method 2 conflict and loss of separation locations

A-6 GV-RINGS Method

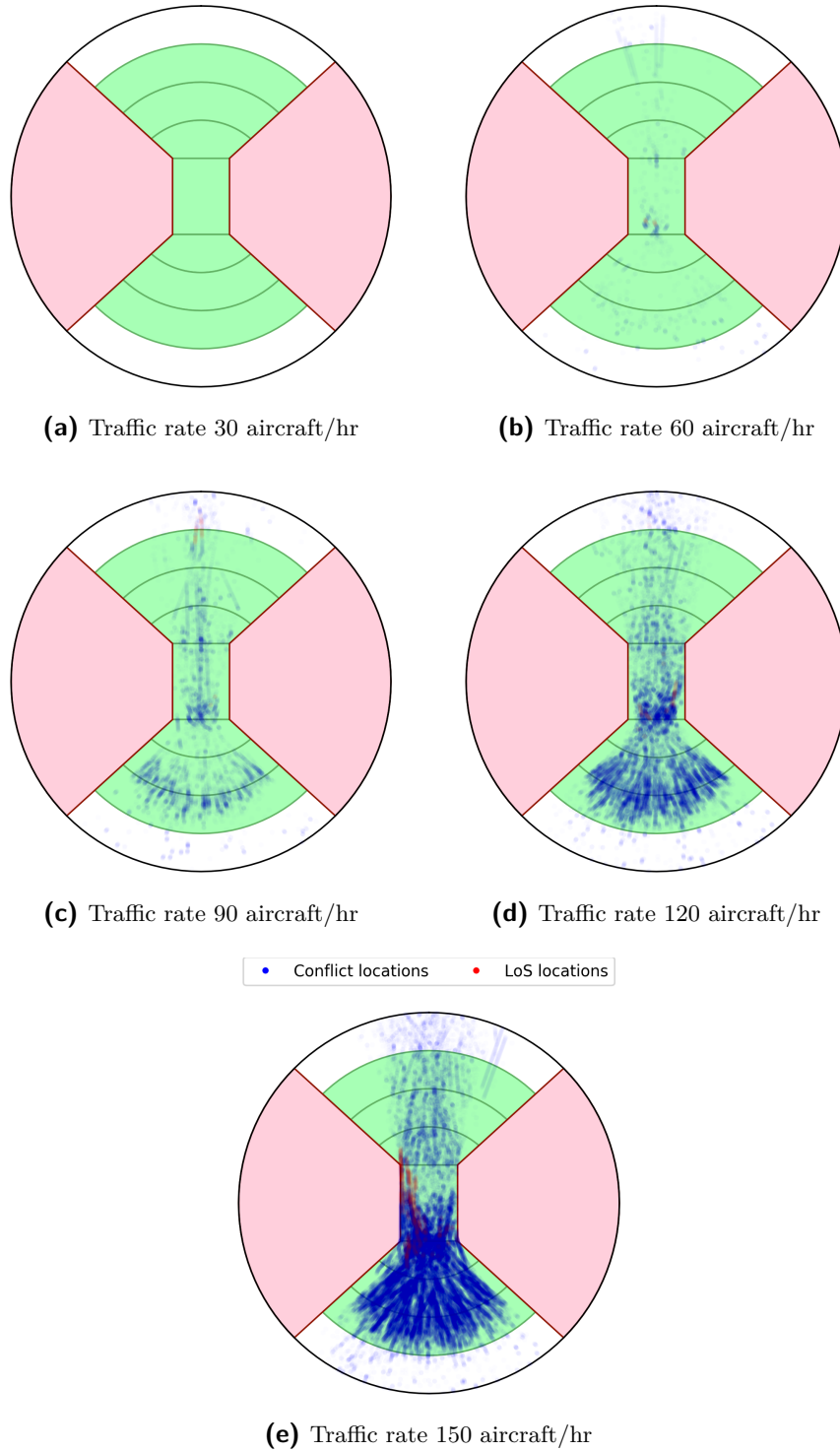


Figure A-6: Geovectoring method 3 conflict and loss of separation locations

A-7 GV-GRID Method

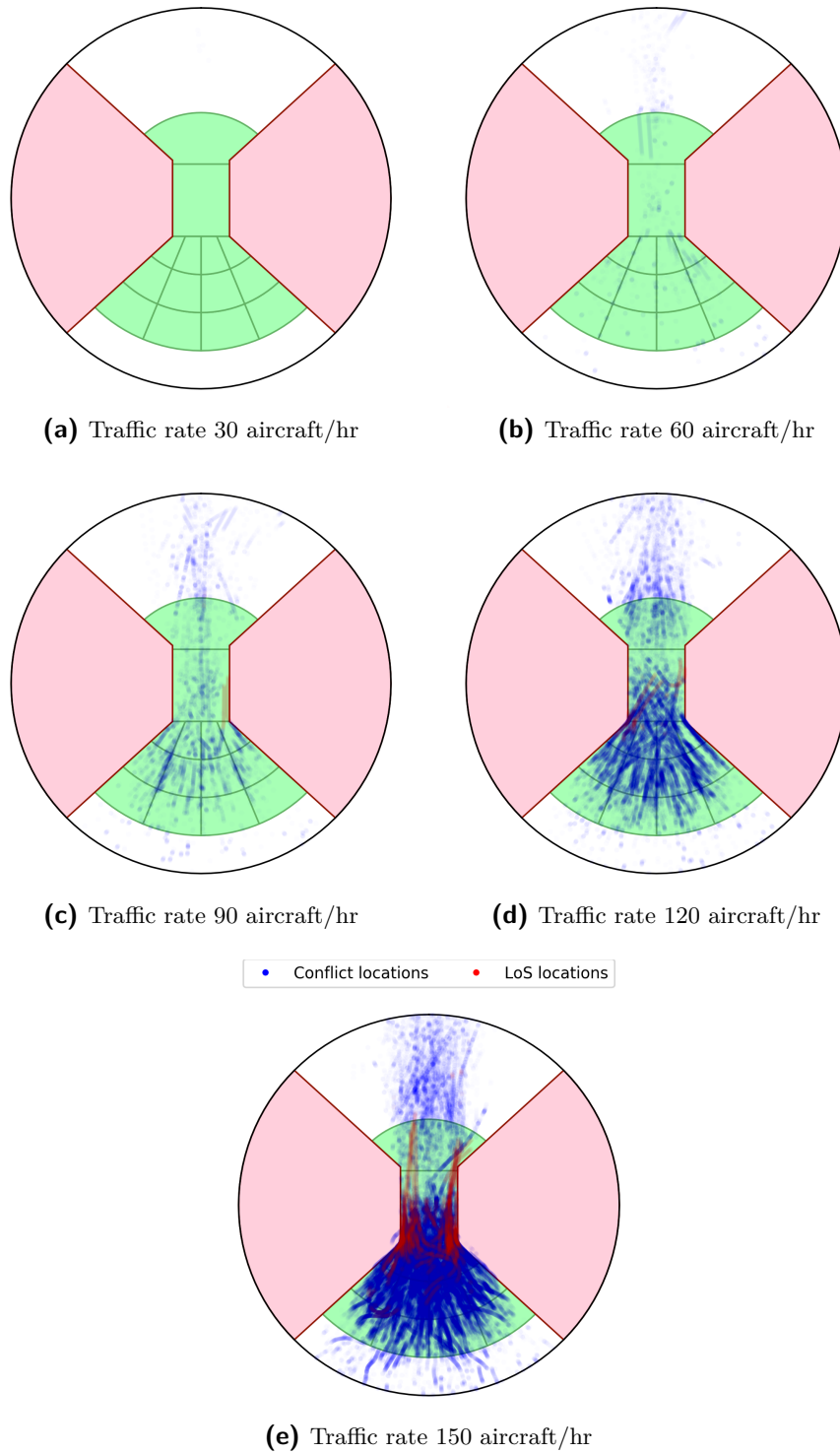


Figure A-7: Geovectoring method 4 conflict and loss of separation locations

Part III

Preliminary report (already graded)

Chapter 1

Introduction

In the past decades the number of commercial flights has grown exponentially. Over the period from 1995 to 2012 the International Civil Aviation Organization (ICAO) reported an average growth of 5.2% per year in the number of Revenue Passenger-Kilometer (RPK) flown from around 2 trillion RPK in 1995 to approximately 5 trillion RPK in 2012 [1]. The organization has predicted that this trend will continue in the coming decades with a forecast annual RPK growth of 4.5% in the period 2012-2042.

Not only is the number of commercial flights growing, but the number of Unmanned Aerial System (UAS) movements is also increasing and it is expected that this trend will continue in the near future. The FAA forecasts that the number of commercial UAS registrations in the United States will increase from 111,000 in 2017 to between 452,000 and 718,000 in 2022 [2]. Integrating the movements of these aircraft into the Air Traffic Management (ATM) system will require the introduction of new technologies and policies [3].

As a consequence of the past and predicted future traffic growth the skies are becoming busier which is putting an increasing strain on the current ATM system. In the present situation almost all air traffic is controlled in a highly centralized fashion with Air Traffic Control (ATC) guidance from the ground. To facilitate this system the airspace is divided into sectors that are each controlled by an Air Traffic Control officer (ATCo) who ensures proper separation between aircraft. One of the factors that constrains the maximum capacity of the system is the workload for each individual ATCo. To reduce this workload the sectors are designed such that the complexity of the traffic flows inside is minimized where possible. However this does often mean that aircraft have to fly a less than optimal route resulting in longer flight times, higher fuel use, and increased emissions.

Within the context of the Single European Skies ATM Research (SESAR) [4] and Next Generation Air Transportation System (NextGen) [5] projects many different approaches to increasing the ATM system capacity to enable future traffic growth are being investigated. One such approach is the Free Flight concept [6] which proposes switching from a centralized system to a decentralized one where cockpit crews will use Self-Separation (SSEP) to avoid other aircraft. How to implement Free Flight and which methods can be used for Conflict

Detection (CD), Conflict Prevention (CP), and Conflict Resolution (CR) [7] are still topics of ongoing research.

One promising method for the implementation of CD and CR using SSEP is the Modified Voltage Potential (MVP) algorithm [8]. This method uses the relative positions and velocities of conflicting aircraft to calculate avoidance vectors on a pairwise basis and sums them to obtain a final avoidance vector. The algorithm has also been tested combined with additional separation rules, such as swarming in unconstrained airspace [9] and leader-following in the presence of airspace restrictions [10]. Another type of rule that could be combined with the MVP is the geovector [11], which imposes constraints on the aircraft velocity vector based on its absolute position.

A specific scenario type in which the use of SSEP has not yet been researched extensively are converging traffic patterns in the presence of airspace restrictions. The presence of these restrictions forces aircraft to all fly routes through the same region, which becomes congested as a result. Examples relevant to commercial air traffic are Restricted Airspace Areas (RAAs) and Weather Hazard Areas (WHAs), whereas for low level UAS traffic ground obstacles such as high rise buildings and other tall structures could also be relevant.

In this research project the use of the MVP method in such constrained situations is studied. The base algorithm is extended using two types of additional steering rules: The first type are rules based on the absolute position of an aircraft; The second type are rules based on the relative position of aircraft with respect to each other. The effects of these MVP extensions on overall performance is studied using various metrics, giving an indication of safety, efficiency, stability, and traffic capacity of the methods. The BlueSky air traffic simulator [12] will be used to perform all simulations necessary for this project.

1-1 Research goals

The aim of the research project proposed in this report is to find out whether it is possible to extend the MVP algorithm in scenarios where traffic flows converge into corridors. The MVP method itself has been studied in various papers, and smaller studies have been performed on the relative position-based swarming and leader-following additions. Research regarding area avoidance for aircraft has been limited, as has research into absolute position-based methods such as geovectoring (on which a first paper was published only in 2018). The integration of these methods into a combined algorithm however has not yet been studied and it is unknown what will be the effects and differences of extending the MVP method with these two types of steering rules. The main objective of the project proposed in this paper is formulated as:

"The goal of this project is to find out whether it is possible to improve the airborne self-separation performance of the Modified Voltage Potential method in converging traffic patterns where airspace restrictions are present by adding absolute and or relative position-based steering behaviors to the algorithm."

It should be noted that the conclusion of this project might be that the proposed additions to the MVP method may not improve the self-separation performance. In pursuit of the research goal stated above the following research question is to be answered:

"Can the addition of extra steering behaviors that depend on either the absolute or relative aircraft positions improve the performance of the Modified Voltage Potential algorithm for

airborne self-separation in situations where airspace restrictions result in convergent traffic patterns?”

This research question is further split up into the two sub-questions given below. The aim of the first sub-question is to investigate how the MVP algorithm could be extended to include the avoidance of airspace restrictions. The objective here is to find a method to accomplish this and study the properties of potential solutions in isolation without adding any other steering behaviors that could improve the traffic flow.

1. Can the MVP method be extended to prevent aircraft from entering restricted airspaces?
 - (a) What method or methods can be used to avoid stationary airspace restrictions?
 - (b) Can these methods be extended to avoid moving obstacles such as weather cells?
 - (c) Is it possible to guarantee that aircraft do not enter restricted airspaces?
 - (d) How do these methods perform for different sizes and shapes of the airspace restrictions?
 - (e) What are the effects of these methods on safety and efficiency?

The second sub-question deals with extending the result from the first part to the investigate the feasibility of improving the MVP performance in presence of airspace restrictions by addition of extra steering behaviors to improve the traffic flow. The goal is to find out if there are differences in performance between adding steering behavior based on the absolute position of traffic and adding steering behavior based on the relative positions of traffic.

2. When extending the MVP method with extra steering behaviors what are the differences between the use of steering behaviors that depend either on the absolute position of aircraft and steering behaviors that depend on the relative position of aircraft?
 - (a) What steering behaviors that depend on the relative positions of aircraft can be added to the MVP algorithm?
 - (b) What steering behaviors that depend on the absolute positions of aircraft can be added to the MVP algorithm?
 - (c) What is the effect of different corridor dimensions on the performance of these methods?
 - (d) What are the effects of these methods on safety and efficiency?
 - (e) Which of the methods is the most effective at preventing conflicts and intrusions?
 - (f) What are the effects of these methods on traffic capacity?

1-2 Outline of this report

This report provides an overview of the work performed during the preliminary phase of the thesis together with the initial results based on this work. The report is structured as follows: In Chapter 2 an overview and review of relevant literature is presented. Using the findings of the literature review a methodology is developed in Chapter 3. Finally, an experiment proposal is made in Chapter 4.

Chapter 2

Literature review

This chapter provides a review of the existing literature that is relevant to the proposed research project. Section 2-1 introduces the different types of airspace restrictions and corridors. An overview of conflict related definitions and classification systems is given in Section 2-2. The technology that enables aircraft to communicate is introduced in Section 2-3. Handling methods for aircraft-to-aircraft conflicts are discussed in Section 2-4 and for aircraft-to-area conflicts in Section 2-5. Section 2-6 introduces two motion behavior rule frameworks. Existing extensions of the MVP method using these frameworks are described in Section 2-7. Relevant results from the Metropolis regarding airspace structure are presented in Section 2-8.

2-1 Airspace restrictions and corridors

Various types of airspace restrictions affect air traffic flows. In this section an overview is given of these restrictions and how their presence can lead to the formation of airspace corridors.

2-1-1 Types of airspace restrictions

There are several types of situations in which parts of the airspace can become unavailable to air traffic. One of the most common types of RAA are Special Use Airspace (SUA)s, which are often used to facilitate operations such as military training exercises, rocket launches and Very Important Person (VIP) movements in a given area while prohibiting conventional air traffic from entering [13], [14]. RAAs are almost always well-defined areas and the activation of these areas is mostly known ahead of time through aeronautical publications.

A different type of airspace restriction can be caused by the formation of convective weather cells which present a safety risk to aircraft. These WHAs are difficult to predict ahead of time as their formation, location, and size depend on wind and weather conditions and vary as a function of time [15]. Due to their hazardous nature they have a large impact on the traffic flows in their vicinity, both in en-route airspace as well as in terminal airspace.

For general aviation and UAS flying outside controlled airspace at lower altitudes there are situations in which they can be prohibited from entering controlled airspace around airports. Even though these airspaces may be available to commercial aircraft or when ATC clearance is given these areas will have to be avoided by general aviation and UAS.

For low-level UAS traffic airspace restrictions can also be present in the form of ground obstacles, which is not a factor for conventional air traffic in most situations. For UAS operations however these obstacles can significantly reduce the airspace that is available, especially in urban environments [16].

2-1-2 Airspace corridor types

Corridors are formed when there are two airspace restrictions near each other that are separated by a part of airspace that is available for aircraft operations. Examples of such situations involving the different types of airspace restrictions described in Section 2-1-1 are presented in Figure 2-1.

Figure 2-1a shows a number of SUAs in the southeastern United States together with the ground tracks of commercial flights. It can be seen that these can cover very large areas and result in relatively narrow corridors that remain available for air traffic.

A number of weather cells around the Atlanta airport are shown in Figure 2-1b. The presence of these cells limits the possible departure and arrival routes to and from the airport. The image only shows the situation at a single point in time, but due to the dynamic nature of weather the geometry and thus the corridors available for air traffic change with time.

An example of a corridor for low-level general aviation traffic between multiple busy airports is shown in Figure 2-1c. A special flight rules area is established over the Hudson and East rivers in New York city, through which low-level traffic can transit through the busy New York airspace in between the Controlled Traffic Regions (CTRs) of the Newark, Kennedy, LaGuardia and Teterboro airports [18].

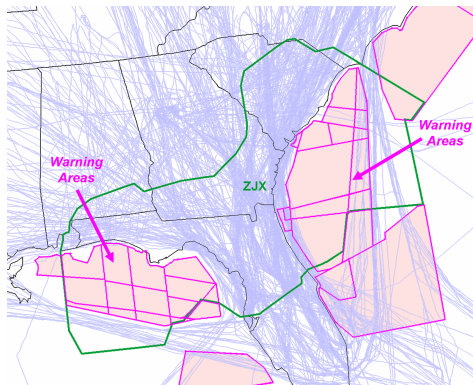
Small-scale, low-level corridors formed by ground obstacles in an urban area are shown in Figure 2-1d. The buildings severely limit the airspace available to UAS traffic and forces all traffic at this level to maneuver through the gaps between the buildings which means that converging traffic patterns are likely to emerge in these areas.

A summary of the most important properties of these different corridor types is given in Table 2-1:

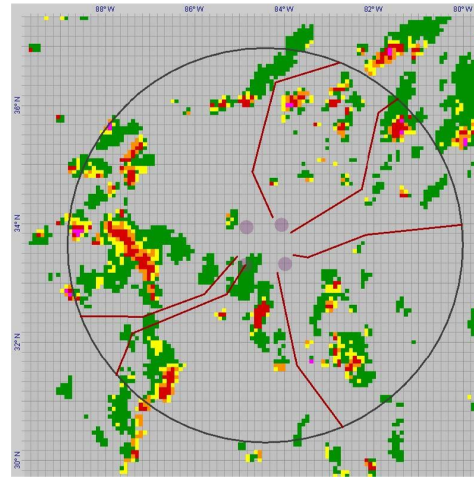
Table 2-1: Summary of properties of different corridor types.

Corridor between	Size	Location	Existence	Most relevant for
RAAs	Large	Static	Dynamic	Commercial aircraft
WHAs	Medium/Large	Dynamic	Dynamic	Commercial aircraft
Controlled airspaces	Medium	Static	Permanent	General aviation and UAS traffic
Ground obstacles	Small	Static	Permanent	UAS traffic

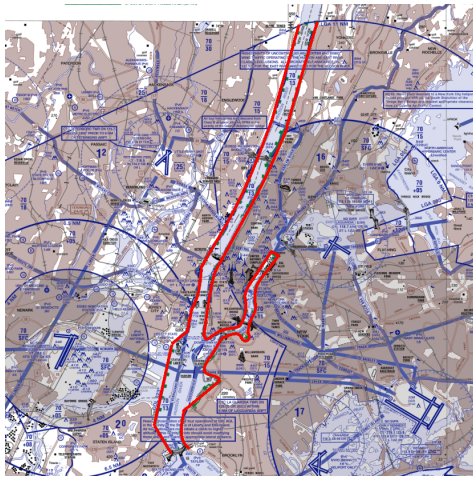
Recent proposals in UAS Traffic Management (UTM) research include various airspace concepts in which different types of traffic are separated using airspace structures. Even



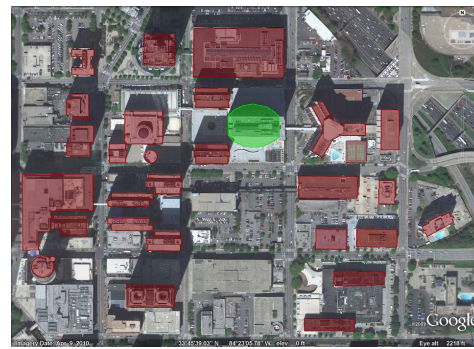
(a) Corridors in en-route airspace formed between SUAs in the south-east of the United States [14, p. 7]



(b) Corridors formed between convective weather cells in terminal airspace near Atlanta [17, p. 5]



(c) Corridors over the Hudson and East rivers formed by the New York Special Flight Rules Area. Adapted from [18, p. 1]



(d) Numerous small-scale corridors for low-level UAS traffic formed between ground obstacles [19, p. 4]

Figure 2-1: Examples of different types of airspace restrictions that can create corridors

though a discussion in further detail is omitted here it is important to note that airspace corridors will likely become more relevant in future studies of airspace designs concepts.

2-2 Conflict prevention, detection, and resolution

To ensure the safety of air travel all commercial flights are currently required to maintain at least a minimum separation from other aircraft at all times. In the current situation the responsibility for maintaining this separation lies with ATCos [20], but in Free Flight concepts these responsibilities are transferred to pilots themselves. This section gives an overview of the definitions of relevant terms and introduces two taxonomies to describe Conflict Detection & Resolution (CD&R) methods.

2-2-1 Conflict and intrusion definitions

There are multiple types of conflicts that are relevant in the current research project. Besides aircraft-to-aircraft conflicts there are two new conflict situations that are introduced based on the findings in Section 2-1: conflicts with non-moving static airspace restrictions such as SUAs and conflicts with moving dynamic airspace restrictions such as weather cells. In the following sections their properties are introduced.

Aircraft-to-aircraft

The properties and definitions used to describe aircraft-to-aircraft conflicts are well established in literature. In literature it is often assumed that commercial aircraft flying at cruise level under Instrument Flight Rules (IFR) are required to maintain a distance of at least 5 Nautical Miles (NMs) horizontally and 1000 ft vertically from other aircraft [7]. This creates a Protected Zone (PZ) around the aircraft (as shown in Figure 2-2) which no other aircraft are allowed to enter.

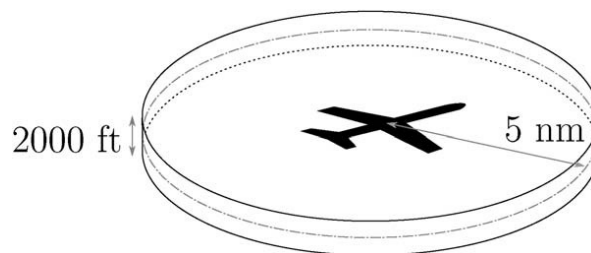


Figure 2-2: The PZ around an aircraft extends 5 NM in all horizontal directions and 1000 ft in both vertical directions. Source: [21, p. 866]

An **aircraft-to-aircraft intrusion** occurs when two aircraft are inside each other's protected zone. Intrusions are also referred to as Loss of Separation (LoS) since the minimum separation criterion of 5 NM horizontally and 1000 ft vertically is not met.

An **aircraft-to-aircraft conflict** occurs when two aircraft are projected to be in a LoS at some point in the future. The number of conflicts detected can be limited by applying a

look-ahead time and only taking into account conflicts where the intrusion is predicted to happen within a given time frame. A value of 5 minutes is often used.

A **multi-aircraft conflict** occurs when one aircraft is in conflict with multiple aircraft at the same time.

Aircraft-to-area

Similar to the definitions of aircraft-to-aircraft intrusions and conflicts given in the previous section the definitions for aircraft-to-area restriction intrusions and conflicts are given below.

An **aircraft-to-area intrusion** occurs when an aircraft is inside the horizontal and vertical boundaries of an airspace restriction.

An **aircraft-to-area conflict** occurs when an aircraft is projected to intrude an airspace restriction at some point in the future. Similar to the aircraft-to-aircraft conflict a look-ahead time can be applied here as well.

2-2-2 Conflict Prevention, Detection, and Resolution

In Section 2-2-1 the definitions of conflicts and intrusions were given. In this section the definitions of three derived concepts are introduced: Conflict Detection (CD), Conflict Resolution (CR), and Conflict Prevention (CP). The definitions given below are adapted from the definitions given by Kuchar and Yang [7].

Conflict Prevention is the examination of the expected trajectories of potential obstacles and determining which ownship maneuvers would create conflicts.

Conflict Detection is the examination of the expected trajectories of potential obstacles and the expected trajectory of the ownship to find conflicts in the near future.

Conflict Resolution is the examination of the expected trajectories of obstacles and determining which ownship maneuvers would resolve conflicts.

In literature the last two are often taken together and referred to as Conflict Detection & Resolution (CD&R). The main difference between the CD&R and CP processes is that the former aims to resolve conflicts as soon as they are detected whereas the latter aims to prevent conflicts from occurring altogether.

2-2-3 Classification systems for different conflict handling methods

A substantial amount of research has been performed to evaluate different methods of handling aircraft-to-aircraft conflicts based on implementations of the concepts introduced in Section 2-2-2. Two classification systems are reviewed in this section.

Kuchar and Yang's classification system

A paper published in 2000 by Kuchar and Yang [7] gave an overview of a number of CD&R methods and introduced a classification system based on the differences in implementation. They organized their classification system based on the implementation of six design factors that are briefly described below.

- **State propagation:** How are aircraft states extrapolated into the future? The classification distinguishes three methods: nominal, worst case, and probabilistic. The nominal case uses linear extrapolation based on the current state, the worst case uses the ensemble of all possible state extrapolations and the probabilistic method uses the probability of each possible extrapolation.
- **State dimensions:** In which plane is the state information used? The classification distinguishes three options: horizontal plane only, vertical plane only, and both horizontal and vertical planes.
- **Conflict Detection:** Does the method use an explicit threshold to identify conflicts? The classification distinguishes two options: yes or no. A threshold can for example take the form of a range criterion or a specified time-to-conflict.
- **Conflict Resolution:** What type of resolution method is used? The classification distinguishes five options: prescribed, optimized, force field, manual, and no resolution. Prescribed methods are fixed during the design of the method and cannot be modified based on changing circumstances. Optimization methods use an algorithmic approach that generally set of possible resolutions based on the minimization of a cost function. Force field methods mimic the behavior of equally-charged particles that repel each other and used this principle to calculate an avoidance maneuver. Manual methods allow the human to specify a resolution that is then checked and evaluated for acceptability. Lastly, some methods can detect a conflict but do not provide a resolution.
- **Resolution maneuvers:** Which type of maneuvers are used to resolve conflicts? The classification distinguishes four options: speed changes, horizontal turns, vertical climb or descent, and combinations of those three.
- **Multiple Conflicts:** How are multi-aircraft conflicts handled? The classification distinguishes two options: pairwise, and global. For pairwise methods each conflict is evaluated individually and the final solution may not guarantee that all conflicts are resolved even if possible. For global methods all conflicts are taken into account and the final solution resolves all conflicts when possible.

Jenie's classification system

More recently in 2017 Jenie et al. [22] developed a classification system aimed mostly at UAS implementations, although it can also be used to describe conventional air traffic. The system is based on the different types of implementation of four factors: airspace surveillance, coordination, avoidance maneuvers, and autonomy. These factors are briefly described below.

- **Type of airspace surveillance:** Three types of surveillance are distinguished: centralized-dependent, distributed-dependent, and independent. In a centralized-dependent system all data is communicated through common stations. In a distributed-dependent system data is communicated between aircraft directly. Lastly, in an independent system there is no direct communication at all but only passive surveillance by each aircraft through its own sensors.
- **Type of coordination:** Three types of coordination are distinguished: explicit, implicit, and uncoordinated. With explicit coordination there is communication between aircraft to resolve a conflict. With implicit coordination there is not communication between aircraft and each uses a common set of rules to resolve a conflict. Lastly, without coordination each aircraft chooses its own preferred conflict resolution actions based on the situation.
- **Type of avoidance maneuvers:** Three types of avoidance maneuver are distinguished: strategic, tactical, and escape. Strategic avoidance aims to resolve long-range conflicts while the intruder is still far away and can be done during flight planning. Tactical avoidance aims to resolve medium-range conflicts using a small maneuver that has only a localized effect on the flight path. Escape maneuvers are short-range, last-resort avoidance measures in which a conflict cannot be resolved and the only objective is to safely avoid a collision.
- **Type of autonomy:** Two types of autonomy are distinguished: manual and autonomous. With manual autonomy a human operator makes the final decision on which actions are to be taken. In autonomous systems the human has no role and the final decision is made by the aircraft systems.

Jenie further states that for various reasons not all possible combinations are viable or even possible options for UAS or conventional applications. This is considered out of scope for this report and the reader is referred to the paper for further elaboration on the feasibility of different methods.

2-3 Automatic Dependent Surveillance-Broadcast

Automatic Dependent Surveillance-Broadcast (ADS-B) is a system that enables the exchange of information between aircraft, ground stations, and (in the future) satellites [23]. It is currently one of the main technological innovations that forms the backbone of the developments in the SESAR and NextGen programs. The system has two components: ADS-B-In for receiving, and ADS-B-Out for transmission of broadcasts. ADS-B has the potential to fully or partially replace the current Secondary Surveillance Radar (SSR)-based systems used by ATC and offers advantages that are not present in the radar-based system.

The system works by means of transceivers that enable users to send and or receive information on the 1090 MHz radio frequency. Messages are send as 'broadcast' meaning that they can be received by all parties that have a receiver and are within range. This enables aircraft to broadcast their state information and receive the state information of surrounding aircraft. In the current ATM system most, if not all, information is only available to the

ATCo on the ground who then relays only part of this information back to pilots. When using ADS-B this information flow is decentralized and available to all nearby parties, which makes the system useful in SSEP scenarios because it removes the dependency on ATC.

ADS-B also has limitations because it depends on the accuracy and precision of aircraft sensors as well as the receivers' ability to correctly decode messages due to range attenuation and interference effects. Langejan [24] investigated the effect of these last two ADS-B system characteristics on the performance of SSEP using the MVP method. It was found that the differences in the application of the MVP method based on sharing state information using ADS-B and the theoretical perfect state information was small, which could make ADS-B a viable candidate for real-world SSEP applications. The experiment concluded that at high traffic densities the interference effect became more limiting than the range effect and that a look-ahead time of five minutes for perfect state information resulted in a close approximation of ADS-B transmissions with a 96 NM range.

Besides transmission of aircraft state information ADS-B technology can also be used to send weather and airspace data to aircraft. In the United States Flight Information Services-Broadcast (FIS-B) is a ground-based broadcast system that operates on the 978 MHz frequency and which is capable of transmitting several different types of information such as: SUA status, weather cell information, weather forecasts and Notice to Airmen (NOTAM) bulletins [25].

2-4 Conflict handling methods for aircraft-to-aircraft conflicts

In sections 2-2-3 and 2-2-3 two classification systems for conflict handling systems were given, but so far no actual examples have been discussed. This section describes several methods relevant to the current research project and makes use of the two taxonomies.

2-4-1 Modified Voltage Potential

The Modified Voltage Potential (MVP) algorithm is one of the central topics of this report and therefore it is key to fully understand the workings of this method. The MVP is an improvement of an earlier algorithm by Eby [26] which was tested and found to be the most effective in a free flight experiment performed by Hoekstra et al. in 2000 [27]. The MVP uses an operating strategy that is analogous to the behavior of equally charged particles in the physical world. Using this method, conflicting aircraft behave similar to these particles and will both steer away from each other.

Using the classification scheme of Kuchar & Yang the MVP method can be categorized as follows: the state propagation is nominal by means of a linear state extrapolation. State information is used in both the horizontal and vertical planes and for CD it uses an explicit threshold in the form of a minimum required distance. For CR the method uses a force field method which results in resolution maneuvers of combined speed, heading, and vertical speed changes. Because the MVP method calculates an avoidance vector for each conflict separately and then sums the resulting vectors it is a pairwise method.

In the Jenie taxonomy the MVP method can be classified as using a distributed-dependent airspace surveillance implementation of direct communication of state between aircraft.

Both aircraft involved in a conflict will perform an avoidance maneuver without explicit coordination, meaning that the coordination for this method is implicit. The type of avoidance maneuver used is tactical avoidance at medium range through calculation of the minimum required velocity change. Depending on the implementation the MVP can be used both manually as well as autonomously which makes it potentially suitable for both UAS and conventional aircraft systems.

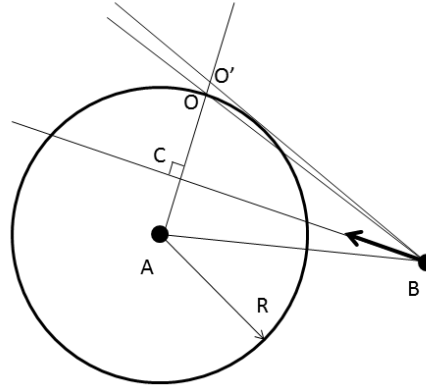


Figure 2-3: Geometry of a conflict as used in the MVP method. Source: [28, p. 59]

The working principle of the MVP algorithm is explained using Figure 2-3. Two conflicting aircraft A and B are shown using a frame of reference that is fixed to A. The circle represents the PZ of aircraft A with radius R . The current relative velocity of intruder B with respect to A means that it will cross the PZ of A in the near future, with the Closest Point of Approach (CPA) of B relative to A being located at point C.

To resolve the conflict the MVP method calculates an avoidance vector perpendicular to the relative velocity vector of B such that the new relative velocity vector of B is tangent to the PZ of A. The new closest point of approach of B relative to A now lies on the edge of the PZ of A and the conflict is resolved. This avoidance vector $\mathbf{V}_{avoid}$ can be computed using Eq. 2-1:

$$\mathbf{V}_{avoid}(t) = \frac{\mathbf{CO}'}{t_{CPA}} \quad (2-1)$$

This vector is then added to the current velocity of B to result in the MVP solution vector that resolves the conflict with A.

$$\mathbf{V}_{MVP}(t) = \mathbf{V}_{current}(t) + \mathbf{V}_{avoid}(t) \quad (2-2)$$

In a multi-aircraft conflict with n conflicting aircraft the MVP solution vector for the ownship consists of the summation of the solution vectors for each individual conflicting aircraft i .

$$\mathbf{V}_{MVP}(t) = \mathbf{V}_{current}(t) + \sum_{i=1}^n \mathbf{V}_{avoid,i}(t) \quad (2-3)$$

When following the avoidance maneuver calculated by the MVP method both aircraft will take evasive action in opposite directions. Consequently the conflict geometry changes over time as the aircraft during the maneuvering, which is why the avoidance vectors are functions of time.

One main advantage of the MVP method is that regardless of the conflict geometry and the amount of conflicts that a given aircraft is in the method is always able to calculate an avoidance vector. The main downside is that this avoidance vector is not guaranteed to resolve all conflicts when in a multi-aircraft-conflict situation.

2-4-2 Velocity Obstacle-based methods

The concept of Velocity Obstacles (VOs) was introduced by Fiorini & Shiller in 1998 [29] as a method to avoid collisions of circular robots. Multiple different methods based on this concept have since been developed, most of which were developed for robotics and some for aviation applications as well. This section aims to give an overview of the definition of a velocity obstacle and two methods based upon it that may be relevant for this project.

Definition of a Velocity Obstacle

The definition of the VO is closely related to that of the Collision Cone (CC). For two aircraft A and B this CC is defined as the set of conflicting relative velocities between A and B. From the perspective of A this means that set of all relative velocities of A with respect to B, $\mathbf{V}_A - \mathbf{V}_B$, that lie on a line $\lambda_{A,B}$ intersecting PZ_B form $CC_{A,B}$ as given in Eq. 2-4:

$$CC_{A,B} = \{\mathbf{V}_A - \mathbf{V}_B \mid \lambda_{A,B} \cap PZ_B \neq \emptyset\} \quad (2-4)$$

Using this definition which is a set of conflicting relative velocities of A with respect to B the VO can now similarly be defined as an equivalent set of absolute velocities of A that conflict with B. This can be done by simply adding the velocity of B, $\mathbf{V}_B$ to each velocity in the set $CC_{A,B}$. Fiorini & Shiller use the Minkowski vector sum operator $\oplus$ to formalize this definition, as given in Eq. 2-5:

$$VO_{A,B} = CC_{A,B} \oplus \mathbf{V}_B \quad (2-5)$$

The CC and VO and their relationship are illustrated in Figure 2-4:

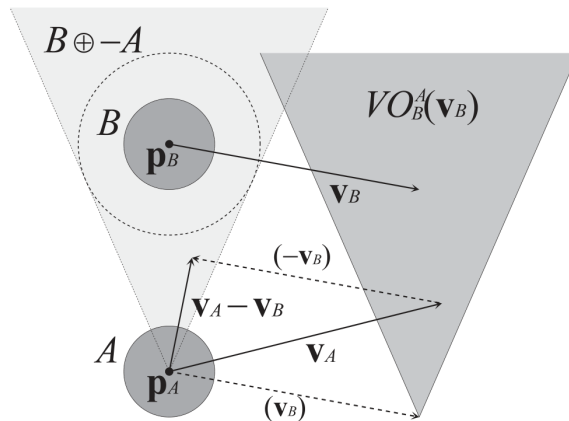


Figure 2-4: The relation between the Collision Cone and Velocity Obstacle. Source: [30, p. 1929]

Because the CC is defined in relative velocity to a given aircraft it is only valid for that specific aircraft. When multiple conflicts are present each CC can be used to find a solution

to that specific conflict only and solutions cannot easily be used to solve all conflicts. However, because the VO is defined using absolute velocities the VOs of multiple conflicting aircraft can be combined and a set of global solutions solving all conflicts can be found.

The Solution Space Diagram method

The Solution Space Diagram (SSD) was first described by Hermes [31] as a tool to support decision making of ATCos. It was later used as a tool to solve conflicts between aircraft, first in simple conflicts with two aircraft ... and later by Balasooriyan in multi-aircraft conflicts [32].

The SSD is based on the combination of two sets of velocities: the Forbidden Velocities FV formed by the union of the velocity obstacles of conflicting traffic and the Reachable Velocities RV , limited by the minimum and maximum speeds of an aircraft. The definitions used by Balasooriyan are given in Equations 2-6 and 2-7:

$$FV = \bigcup_{i=1}^n VO_i \quad (2-6)$$

$$RV = \left\{ (x, y) \in \mathbb{R}^2 \mid x^2 + y^2 \geq V_{\min}^2, x^2 + y^2 \leq V_{\max}^2 \right\} \quad (2-7)$$

These base definitions can be used to define the sets of Allowable Reachable Velocities ARV and Forbidden Reachable Velocities FRV :

$$ARV = RV \cap FV^C \quad (2-8)$$

$$FRV = RV \cap FV \quad (2-9)$$

The union of these two sets makes up the complete SSD. An example of the construction of the SSD based on the four sets FV , RV , ARV , and FRV is shown in Figure 2-5:

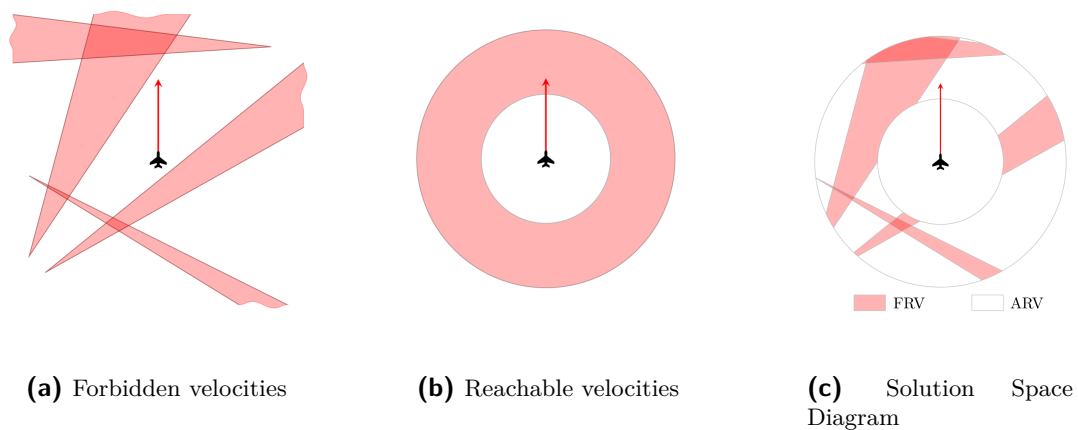


Figure 2-5: Visualization of the construction of the SSD. Source: [32, p. 71]

Compared to the MVP method which prescribes a single maneuver the SSD results in a set of velocities that solve all conflicts. However, because the SSD method uses the union

of individual VOs it is not guaranteed that $ARV \neq \emptyset$ and a solution vector that solves all conflicts may not exist.

When a set of solutions that solves all conflicts does exist there are many different avoidance strategies that can be used. An example of a conflict situation using different coordination rules with solutions found using the SSD is given in Figure 2-6. It should be noted that the third solution is not an SSD solution but implicitly expects the intruding aircraft to solve the conflict based on priority rules specified in the rules of the air [33].

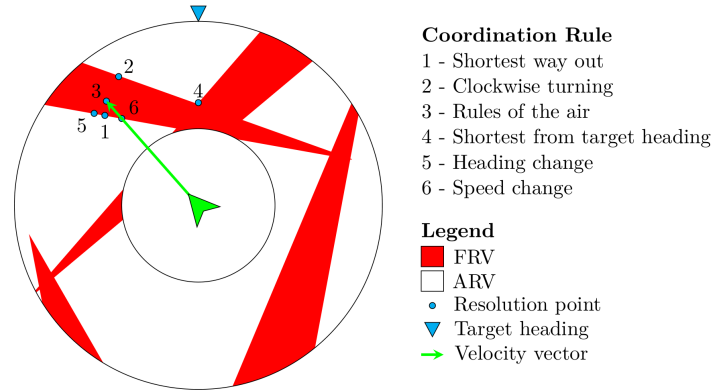


Figure 2-6: Examples of solutions based on different coordination rules as proposed by Balasooriyan. Source: [32, p. 77]

Using the classification scheme of Kuchar & Yang the SSD method can be categorized as follows: the state propagation is nominal by means of a linear state extrapolation. State information is used in only the horizontal plane and for CD it uses an explicit threshold in the form of a minimum required separation. For CR the method results in a set of possible resolution maneuvers of combined speed and heading changes (if such a set of solutions exists). Because the SSD method calculates an avoidance vector for all conflicts at once it is a global method.

In the Jenie taxonomy the SSD method can be classified as using a distributed-dependent airspace surveillance implementation of direct communication of state between aircraft. Both aircraft involved in a conflict will perform an avoidance maneuver without explicit coordination, meaning that the coordination for this method is implicit. The type of avoidance maneuver used is tactical avoidance at medium range through calculation of a set of resolution velocities. Depending on the implementation the SSD can be used both manually as well as autonomously which makes it potentially suitable for both UAS and conventional aircraft systems.

The Selective Velocity Obstacle method

The Selective Velocity Obstacle (SVO) concept was proposed by Jenie et al in 2015 [34] as a collision avoidance method for UAS applications. However, the method could also be applied to commercial aircraft. It is based on the VO concept and generates a deconflicting maneuver that tries to keep the deviation from the original route as small as possible.

The basis for the SVO concept lies in the rules of the air [33] from which it uses the right-of-way rules that determine when an aircraft that is in conflict has the right of way and when

it has to maneuver to avoid. The method uses the relative velocity of an intruding aircraft with respect to the ownship to determine whether the ownship has to maneuver or can stay its course.

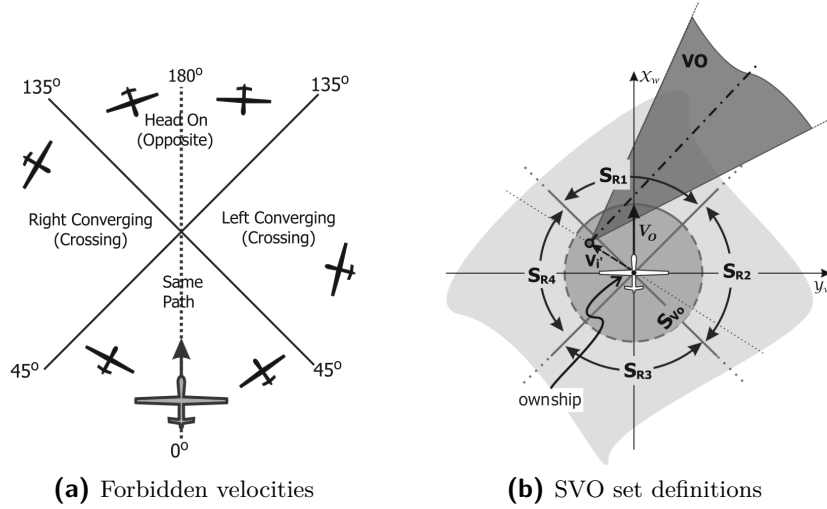


Figure 2-7: Visualization of conflict types and relationship with the VO used by the SVO method.
Source: [34, p. 1142]

There are five possible types of conflict, shown in Figure 2-7a: Same path where the ownship is being overtaken, Same path with the ownship overtaking the intruder, Right converging, Head on, and Left converging. The SVO method defines four sets of relative velocities S_{R1} , S_{R2} , S_{R3} , and S_{R4} used to distinguish these five conflict types as shown in Figure 2-7b. The location and orientation of the intruders VO with respect to these four sets determines the type of conflict and the rules of the air then prescribe whether or not a maneuver has to be made.

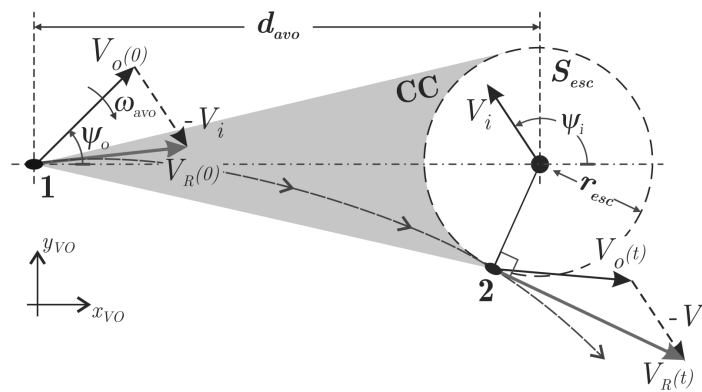


Figure 2-8: Visualization of a minimum turn rate maneuver prescribed by the SVO method.
Source: [34, p. 1142]

In the situations where the distance to an intruder becomes smaller than the minimum avoidance distance d_{avo} and the ownship does not have right-of-way a maneuver has to be made. An example of such a situation is shown in Figure 2-8. At point 1 a conflict is detected

and a minimal turn-rate avoidance maneuver is started. The curved arrow is the velocity of the ownship relative to the intruder $V_R(t)$ and it can be seen that at point 2 this velocity lies tangent to the PZ of the intruder S_{esc} and a minimum separation r_{esc} is achieved.

Using the classification scheme of Kuchar & Yang the SSD method can be categorized as follows: the state propagation is nominal by means of a linear state extrapolation. State information is used in only the horizontal plane and for CD it uses an explicit threshold in the form of a minimum required distance between aircraft. For CR the method prescribes a turn with minimum avoidance turn rate. For multi-aircraft conflicts the SVO method uses the union of the intruders' VOs to calculate an avoidance maneuver and is thus a global method.

In the Jenie taxonomy the SVO method can be classified as using a distributed-dependent airspace surveillance implementation of direct communication of state between aircraft. Both aircraft in a conflict will use the relative geometry of a conflict to determine whether or not they have to perform an avoidance maneuver without explicitly coordinating, meaning that the coordination for this method is implicit. The type of avoidance maneuver used is tactical avoidance at medium range through calculation of a minimum turn rate. Depending on the implementation the SVO can be used both manually as well as autonomously which makes it potentially suitable for both UAS and conventional aircraft systems.

2-5 Conflict handling methods for aircraft-to-area conflicts

In the previous section a number of conflict handling methods for aircraft-to-aircraft conflicts was discussed. In this section an overview for aircraft-to-area conflicts is given.

There is a distinct difference between the two conflict types: Aircraft-to-aircraft conflicts are mostly ad hoc situations with a relatively small amount of warning time and are not easily predictable ahead of time whereas aircraft-to-area conflicts are usually known ahead of time. Airspace restrictions are published hours or days ahead of time and are known during flight planning but the weather cells are more dynamic and their existence and location are continuously tracked and their properties change relatively slowly. In the current ATM system aircraft-to-area conflicts are thus either avoided during flight planning or using radar vectors provided by ATC. Consequently most literature on these topics consists of various route-planning methods.

In a free-flight environment there will be no ATC to provide radar vectors around RAAs and WHAs. Even when aircraft routes are planned to avoid entering these areas there is still the potential for maneuvers resulting from aircraft-to-aircraft conflicts to result in ad hoc aircraft-to-area conflicts.

Chakravarthy et al showed that the CC principle discussed in Section 2-4-2 can be applied to irregularly shaped static obstacles [35]. This means that it is possible to generate a CC for non-moving obstacles encountered by aircraft such as RAAs. Also, using the Velocity Obstacle definitions seen in Section 2-4-2 it becomes possible to extend Chakravarthy's theory to enable the creation of Velocity Obstacles for irregularly shaped moving obstacles such as WHAs.

Two examples of irregular static objects and the resulting collision cones are shown in Figure 2-9. For non-moving obstacles these collision cones could be used to restrict the allowable heading ranges of aircraft to avoid these areas. For moving obstacles the collision cones

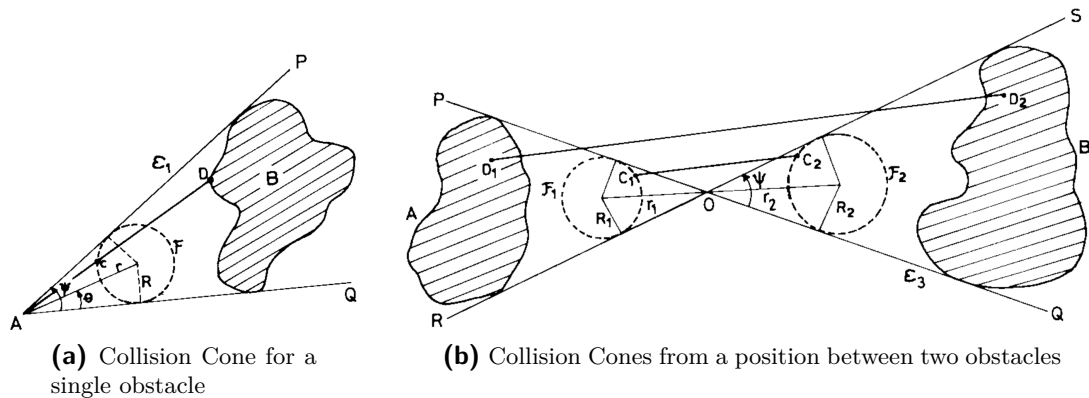


Figure 2-9: Collision Cones defined by irregularly shaped obstacles. Source: [35, pp. 568-569]

cannot be used directly but instead the velocity obstacles would have to be used to find allowable combinations of heading and speed. This adds an extra dimension to the problem and solutions could resemble strategies also seen in the SSD method described in Section 2-4-2.

2-6 Motion behavior rules

Motion rules and steering behaviors can be described using the frameworks introduced in this section. Section 2-6-1 introduces a motion behavior hierarchy and classification of steering behaviors for general purpose autonomous agents. A geovectoring framework to limit the allowable motion of airborne vehicles is introduced in Section 2-6-2.

2-6-1 Reynolds' motion behavior hierarchy

In 1997 Craig Reynolds published a paper on motion steering behaviors for autonomous characters [36]. Reynolds describes a number of simple behaviors that can be combined to result in complex actions taken by these agents. The theory can also be applied to aircraft simulation, where the autonomous agents are represented in the form of individual aircraft whose actions can be described using the steering behaviors.

Reynolds divides the behavior of autonomous agents into a three layered hierarchy: Action Selection, Steering, and Locomotion. The Action Selection layer encompasses the goal of the behavior, the Steering layer splits this goal up into sub-goals that are used to describe how the goal will be accomplished, and Locomotion layer implements these behaviors through an agent model including dynamics. The relationship between the three layers is shown in Figure 2-10.

Reynolds' paper focuses mostly on the steering layer of the behavior hierarchy and gives several examples of steering behaviors that accomplish different subgoals. The steering behaviors can be split into three categories: individual, relative to another actor, and combined behaviors. A brief overview of descriptions is presented below, for visual representations the reader is referred to Reynolds' paper.

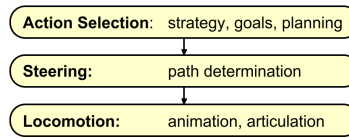


Figure 2-10: Reynolds' motion behaviors hierarchy. Source: [36, p. 764]

The first category is that of individual steering behaviors, these do not depend on the presence of other actors. The following behavior types are distinguished by Reynolds: **Seek** is the behavior of steering towards a static point but not stopping when reaching the point. **Flee** is the inverse of Seek and results in movement radially outward from a given point. **Arrival** is the behavior of steering towards a location and ending at this location with zero relative velocity. **Obstacle Avoidance** is the behavior that steers to avoid colliding with non-actor obstacles. **Wander** is a probabilistic steering type where the direction of movement is changed by a random value obtained using a given probability distribution. **Path following** is the behavior where the agent follows the center-line of a predefined path while remaining within a specified distance to the path. **Wall following** is similar to path following with the additional restriction that the agent has to remain on one side of a wall. **Containment** is a type of behavior where the movement is limited to a certain area. Lastly, in **Flow-field following** the direction of motion is determined by the position of the agent.

The second category is where the steering behavior of an agent is related to the position and/or motion of another agent. **Pursuit** is similar to Seek with the main difference that the target is the future position of another agent at a specified time. **Evasion** is the opposite of Pursuit and is used to steer away from the future position of another agent. **Offset pursuit** is similar to the Pursuit behavior but aims at a point that has a specified offset distance from a moving target agent. **Unaligned collision avoidance** is the behavior where actors that are moving in random directions attempt to steer away from each other to avoid collisions. **Separation** is the steering behavior where an agent attempts to maintain a given distance to another agent that is moving in a similar direction. **Cohesion** is the behavior where an agent steers towards the average position of a number of other agents moving in similar directions. **Alignment** is the behavior where an agent steers in the average direction of other agents that are nearby.

The last category is that of combined steering behaviors which are made up of combinations of individual steering behaviors and steering behaviors based on other agents. There are two main methods of combining behaviors: executing multiple steering actions in parallel and executing steering behaviors sequentially. A system of rules and relative priorities can be used to determine the relative weights of steering actions in parallel combinations and to determine when to switch behavior modes in sequential combinations. Many different combinations can be used to achieve different results; the four main combined behaviors described by Reynolds are summarized here: **Flocking** is the parallel combination of separation, cohesion and alignment behaviors to create a group of agents that move in a given direction as a group. **Leader-following** is the combination of arrival and separation behavior where an agent steers to follow another agent but maintains a given minimum distance. **Interpose** uses pursuit and seek to steer towards a point between two other agents. **Shadowing** is similar to leader-following where the shadowing agent maintains separation and moves in the same direction as the leader, but does not follow in its track.

2-6-2 Geovectoring

Geovectoring is a new concept introduced in 2018 by Hoekstra et al. [11] as a method to increase airspace capacity for UAS operations. The principle used in this concept is limiting the allowable ranges of heading, ground speed, and vertical speed at which an aircraft is allowed to fly inside a specified geographic region. This can also be applied to commercial aviation, which means that the concept is not limited to UAS applications only.

The geovectoring concept is related to the geofencing and geocaging concepts as shown in Figure 2-11. While the geofencing and geocaging concepts can be used to influence the static traffic density the geovectoring concept can be used to influence the dynamic traffic density.

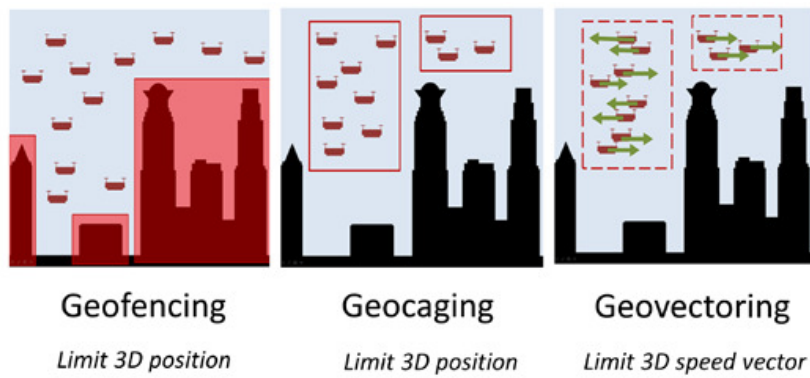


Figure 2-11: [Visualization of the relationship between geofencing, geocaging, and geovectoring concepts. Source: [11, p. 5]

These concepts can be used to reduce conflict rates and increase airspace capacity using two mechanisms:

- **Airspace segmentation** through the use of geofencing and geocaging can reduce the global conflict rate by limiting the interaction between different traffic flows through geographic separation.
- **Reduction of relative velocities** through the use of geovectoring can reduce the local conflict rate by limiting the distribution of the velocity vector values inside a given region.

The mathematical definition of a geovector given by Hoekstra defining the allowed intervals of the three velocity vector components as a function of latitude, longitude and altitude is given by Eq. 2-10:

$$\mathbf{V}_{geo} = \begin{pmatrix} GS \\ \chi \\ VS \end{pmatrix} = \begin{pmatrix} [GS_{min}, GS_{max}] \\ [\chi_{min}, \chi_{max}] \\ [VS_{min}, VS_{max}] \end{pmatrix} = f(lat, lon, altitude) \quad (2-10)$$

A visual representation of a given set of allowed intervals is give in Figure 2-12. In this example, the ground speed is limited to 250 knots, the heading is limited to a range of 180-360 degrees, and the vertical speed is limited to a range of -500 to +500 feet per minute.

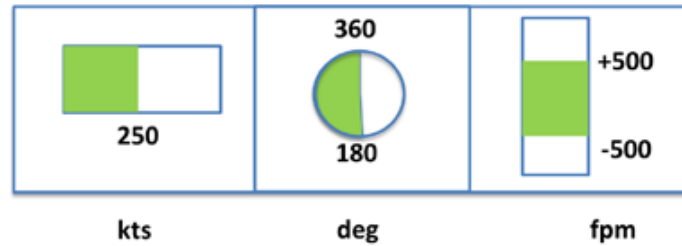


Figure 2-12: Visual representation of the geovector allowable ranges (green) of the velocity vector components. Source: [11, p. 5]

A geovector does not necessarily have to impose constraints on all components of the velocity vector and depending on situational requirements any subset of the three components can be constrained while keeping the full range for the remaining components available.

Hoekstra defines two different geovector types: static and dynamic. The former do not change over a longer time period and could be implemented using a simple navigation database. Dynamic geovectors can vary as a function of time which may require them to be broadcast to aircraft in real-time.

2-7 Relevant previous work extending the MVP method

The idea of extending the MVP algorithm with extra steering rules is not new and a few examples can be found in literature. In this section two existing modifications are discussed: the MVP method extended with leader-following behavior and the MVP method extended with swarming behavior.

2-7-1 Extension of the MVP method with Leader-following behavior

In 2009 Kieskamp [10] extended the MVP algorithm using steering rules based on Reynolds' leader-following behavior type. The aim of his experiment was to improve the performance of the MVP algorithm used for self-separating en-route air traffic in the presence of airspace restrictions. The method can be divided into four sequential phases: Conflict detection, conflict type determination, conflict resolution, and recovery. The working principles of these phases are presented below. Based on the leader-following behavior type each aircraft is either classified as 'leader' when it is not following any other aircraft, or as 'follower' when it is following a leader.

Phase I: Conflict detection

In the first phase the conflict detection is done in the same way as the original MVP algorithm. For each aircraft the time to closest point of approach and minimum distance relative to an intruder is calculated using a linear state extrapolation. If this distance is smaller than the radius of the intruder's PZ then the pair is in conflict.

Phase II: Conflict type determination

When a conflict is detected in the first phase its type needs to be determined. To do this, three factors are evaluated for each conflict:

- The relative directions of the conflicting aircraft pair with respect to each other. This is determined by the angle between the velocity vectors. If this is less than 90 degrees the relative direction is defined as ‘quasi-equal’ and for larger differences it is defined as ‘quasi-opposite’.
- The status of the ownship (leader or follower). This is determined by finding the point of first intrusion on the edge of the PZ of the intruder. The PZ can be divided into two ‘hemispheres’ by a line through the aircraft perpendicular to the velocity vector. If the point of first intrusion lies in the forward hemisphere the ownship status is that of ‘leader’, otherwise it is that of ‘follower’.
- The status of the intruder (leader or follower). Determined in the same way as the status of the ownship.

Based on the relative direction and both aircraft statuses the conflict resolution method that must be used is specified in Table 2-2. For quasi-opposite conflicts the MVP method is used to resolve, regardless of the status of either aircraft.

Table 2-2: Conflict resolution method used based on conflict direction and status of ownship and intruder.

Direction	Ownship status	Intruder status	Resolution method
Quasi-opposite	Leader or Follower	Leader or Follower	MVP
Quasi-equal	Leader	Leader	MVP
Quasi-equal	Follower	Leader	Leader-following
Quasi-equal	Leader	Follower	Leader-following
Quasi-equal	Follower	Follower	MVP

To prevent aircraft that are turning from causing a ripple effect during their maneuver a 30 second threshold filter is used for conflict resolution. This means that once a conflict is detected aircraft will only start to take evasive action once the conflict has been going on for 30 seconds.

Phase III: Conflict resolution

Once the conflict type has been detected and the conflict resolution phase begins either the MVP or the Leader-following method is used. Their characteristics are summarized below.

Using the MVP method: the procedure is almost the same as was described in Section 2-4-1. The only difference is the use of the 30 second filtering threshold described in the previous section.

Using the Leader-following method: the conflict resolution procedure is more complicated. The prescribed action depends on the aircraft status as well as the time to closest point of approach.

- **As leader:** When an aircraft has the status of leader the leader-following method prescribes that it does not take any evasive action.
- **As follower:** The look-ahead time used to detect conflicts is split into two parts: in the first 60 seconds the follower attempts to resolve the conflict using following behavior by aiming its velocity vector at the point on the leaders PZ opposite of its velocity direction. A visual representation of this maneuver is given in Figure 2-13. If the conflict is not resolved in this way within these 60 seconds the follower will revert to using the MVP method to resolve the conflict.

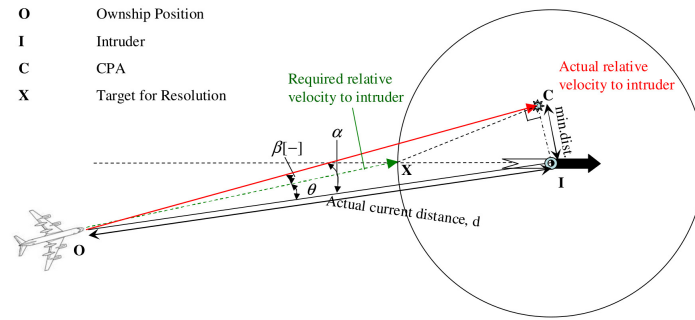


Figure 2-13: Conflict resolution prescribed for aircraft with follower status by the leader-following method. Source: [10, p. 82]

An optional follow-through mode is introduced, where an aircraft that is following a leader has resolved the conflict using the leader-following method will attempt to continue to follow the leader aircraft. This mode is then maintained until one of the following four switch-off conditions is met:

- The follower has achieved a stable state where difference in course and relative velocity with the leader is minimal.
- The follower is no longer able to follow the heading of the leader.
- The follower has entered the protected zone of the leader.
- The follower has had to change its heading direction three consecutive times.

Phase IV: Recovery

The recovery phase is where the aircraft goes back to its original heading that it had before the conflict. This phase is entered in one of the two following circumstances:

- After conflict resolutions when a conflict has been solved.
- After follow-through maneuvering where a stable flight condition has been reached.

Experiment results

In the experiment the leader-following method both with and without the follow-through module enabled was compared to the MVP in both unconstrained and constrained airspace. It was found that in unconstrained airspace the basic leader-following method performed better than both the MVP and the leader-following method with follow-through enabled. However, in constrained airspace the latter performed better than both the MVP and basic leader-following method. It has to be noted that the metrics used by Kieskamp are different than the metrics used in most current air traffic analyses which makes it difficult to make direct comparisons with results from other experiments.

2-7-2 Extension of the MVP method with swarming behavior

Another method of extending the MVP algorithm with extra steering rules is the Swarm Augmented Modified Voltage Potential introduced by Maas et al. [37] who make use of Reynolds' swarming behavior type. The method aimed to improve the performance of the MVP method for en-route traffic in unconstrained airspace and consists of three separate steering behaviors that are executed in parallel: Collision Avoidance, Velocity Alignment and Flock Centering. A set of weights and criteria is used to determine the behavior types that should be used and their relative importance at any given time. An overview of the working principles is given below.

The collision avoidance element is implemented using the MVP algorithm described in Section 2-4-1. For each aircraft a resolution vector is continuously calculated based on any detected conflicts. When no conflicts are present the vector simply points in the direction of an aircraft's target heading, such that a resolution vector always exists and can be used in the weighing process.

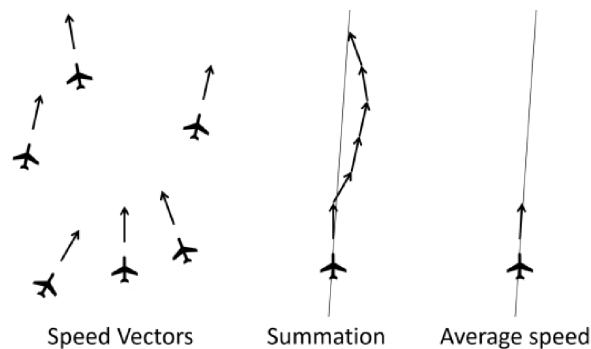


Figure 2-14: Averaging of the velocity vectors in the velocity averaging process. Source: [37, p. 2]

The velocity alignment element takes the velocity vectors of nearby traffic surrounding an aircraft (including itself) within a given radius and calculates the average of these velocities. This average is then prescribed as resolution vector for this behavior type. A visualization of this process can be seen in Figure 2-14.

The flock centering element is implemented by calculating the average position of nearby traffic surrounding an aircraft (including itself) within a given radius. A resolution vector

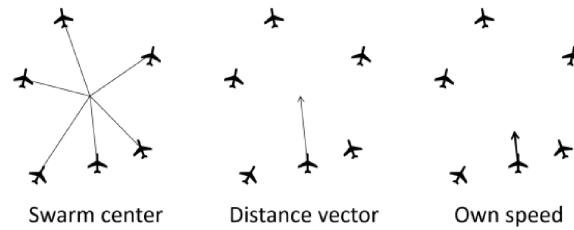


Figure 2-15: Calculation process for the velocity vector pointing towards the center of the flock.
Source: [37, p. 3]

with the aircraft's current speed is then prescribed in the direction to this average position. A visualization of this process can be seen in Figure 2-15.

The resolution vectors from these three elements are then used in a weighted average to obtain the final resolution vector prescribed by the swarming augmented method. The weights used by Maas are given in Table 2-3:

Table 2-3: Weight values used to calculate the final resolution vector in the Swarm Augmented Modified Voltage Potential method.

Swarming element	Weight value
Collision avoidance	10
Velocity alignment	3
Flock centering	1

The velocity alignment and flock centering elements use a set of three criteria that determines which surrounding aircraft are included in the calculations for these elements. Maas reports using the following criteria:

- Horizontal distance to the ownship should be less than 7.5 nautical miles.
- The vertical distance to the ownship should be less than 1500 feet.
- The relative difference in heading with respect to the ownship should be less than 90 degrees.

Maas states that the weight values and the values used for the flock criteria are all based on experimental results and were set by trial and error.

Experiment results

The Swarming Augmented MVP method was compared to the original MVP algorithm as well as a baseline without any form of CR in a simulation of an unconstrained en-route airspace with traffic moving in all directions. It was found that the Swarming Augmented MVP method performed worse than the original MVP method on all metrics. Compared to the MVP method the extra steering rules reduced route efficiency and generated more conflicts and losses of separation.

2-8 The Metropolis project

The metropolis project was a research effort aimed to “investigate the influence of airspace structure on capacity, complexity, safety, and efficiency for high-density airspace” [38]. Although the project only considered an urban environment with high density UAS and Personal Air Vehicle (PAV) traffic the observations are also relevant to self-separating commercial aircraft in the en-route phase. Four different airspace structure concepts were tested with increasing degree of structure: full mix, layers, zones, and tubes. For the first three concepts the MVP algorithm was used for CD&R while for the last concept time-based separation is used.

An overview of the four different airspace structure is shown in Figure 2-16.

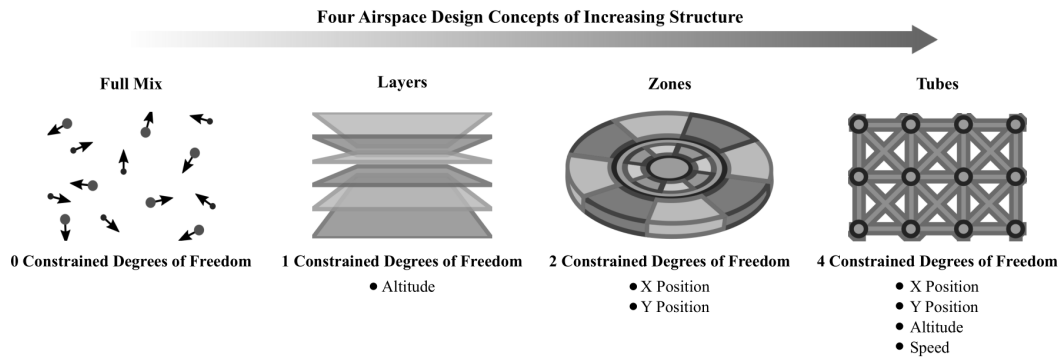


Figure 2-16: The four airspace structure concepts and their constraints on aircraft's degrees of freedom. Source: [39, p. 40]

The four concepts can be summarized as follows:

- **Full mix concept:** Aircraft are free to choose their most optimal horizontal route and vertical profile. Conflict resolution maneuvers are allowed to take the form of heading, speed, and altitude maneuvers or combinations thereof.
- **Layers concept:** Aircraft are free to choose their most optimal horizontal route but are limited to different altitude bands based on their heading. Conflict resolution maneuvers are only allowed to take the form of speed and or heading changes.
- **Zones concept:** Aircraft are free to choose their most optimal vertical profile but are limited to certain zones based on their heading. Conflict resolution maneuvers consist of speed and altitude changes only. For conflict detection only conflicts within the same zone and merging areas are considered.
- **Tubes concept:** Aircraft routes are conflict-free and pre-planned in space and time through tubes that connect at nodes. All aircraft at a given level fly at the same speed to simplify separation.

In the experiment UAS and PAV traffic flew at different altitude ranges during the cruise phase, with the UAS traffic occupying low-level altitudes and the PAV traffic higher-level

altitudes. The two traffic types only conflicted with each other during the takeoff and landing phases.

The study found that the layers concept resulted in the best balance between safety and efficiency. The tubes and zones concepts had the higher numbers of conflicts and intrusions per flight and lower route efficiency compared to the full mix and layers concepts. It was concluded that “A consistent improvement of Full Mix and Layers over Zones and Tubes indicates that capacity at extreme densities benefits from little structuring of the airspace”.

A conflict rate model for layered airspace

In a subsequent paper Hoekstra et al. [40] present a model that describes the effects of the layering concept on global conflict rates. The model is a combination of three separate effects that can be seen in the concept:

- **Spreading effect:** through vertical segmentation aircraft can only conflict with traffic that is cruising in the same altitude layer. For this model it is assumed that there is no climbing/descending traffic.
- **Reduced relative velocity effect:** through limiting the allowable heading range in an altitude layer the relative velocities between aircraft in a given layer are smaller than in a full-mix situation. This reduces the probability of conflicts in a given layer.
- **Other effects:** these are unrelated to the layering concept and include factors such as airspace size, average aircraft velocity, minimum separation distance etc. that would also be present if the airspace was not split into layers.

The model for the global conflict rate proposed by Hoekstra is given in Eq. 2-11. The contributions of the effects described above can clearly be seen:

$$CR_{global} = \underbrace{\frac{1}{2}N\left(\frac{N}{L} - 1\right)}_{\text{Spreading effect}} \cdot \underbrace{\frac{1}{\alpha}\left(1 - \frac{2}{\alpha}\sin\left(\frac{\alpha}{2}\right)\right)}_{\text{Reduced relative velocity effect}} \cdot \underbrace{\frac{\bar{V} \cdot R \cdot T_{FL}}{A \cdot T_{tot}}}_{\text{Other effects}} \cdot k \quad (2-11)$$

In this equation CR_{global} is the global conflict rate, N is the number of aircraft, L is the number of altitude layers, α is the range of allowed headings, $\bar{V}$ the average velocity, R the minimum separation distance, T_{FL} the time spent in the airspace, A the airspace area, T_{tot} the total experiment time, and k is a constant for airspace structure effects. It is noted by Hoekstra that this last element k is not yet understood very well.

Tra et al. [41] validated this model and looked at the effects of varying the allowable heading range per layer and the effect of airspeed distribution. Tra also added terms to include 3-dimensional effects of climbing and descending traffic. These extra terms are not considered in greater detail here and only the heading and airspeed distribution effects will be discussed for scenarios without climbing and descending traffic.

It was found that the model was able to accurately predict the conflict rate at higher traffic intensities by extrapolating from experimental observations made in lower density scenarios, indicating that the base assumptions seem valid. A small difference between theory and

observation that was observed could possibly be explained by the difference in CD methods between model and simulation. It was also observed that the model is less accurate when the actual heading distribution of aircraft in a simulation is not the same as the assumed theoretical distribution.

The effect of allowable heading ranges per layer was found to be in agreement with the model prediction. The effect of the layers was seen in the 360°-layer scenario where all heading ranges were allowed in all layers, but the existence of the layers resulted in a much lower conflict rate compared to unstructured airspace. Similarly, reducing the allowable heading range per layer significantly reduced conflict rates at all densities with respect to the 360°-layer scenario.

2-9 A capacity model for self-separation methods

In 2018 Sunil et al. [42] proposed a new analysis tool: Capacity Assessment Method for Decentralized Air Traffic Control (CAMDA). This is a semi-empirical method that can be used to determine the maximum theoretical capacity of SSEP implementations. It derives a relationship between the Domino Effect Parameter (DEP) [43] and the maximum airspace capacity.

The DEP gives a measure of the ability of a SSEP method to prevent conflict resolutions from causing ‘chain reactions’ of new conflicts and is defined in Eq. 2-12.

$$DEP = \frac{C_{total,wr}(\rho)}{C_{total,nr}(\rho)} - 1 \quad (2-12)$$

In this equation ρ is the traffic density, $C_{total,wr}$ is the number of conflicts with CR off, and $C_{total,nr}$ is the number of conflicts using a SSEP method for CR. The CAMDA method relates this to the maximum theoretical airspace capacity ρ_{max} using Eq. 2-13:

$$\lim_{\rho \rightarrow \rho_{max}} \frac{dDEP(\rho)}{d\rho} = \infty, \text{ where } \rho_{max} \equiv \text{capacity} \quad (2-13)$$

When this capacity is reached the resolution action of any aircraft would influence all other aircraft and solving conflicts is no longer possible. Instead, aircraft would be in avoidance maneuvers continuously and could no longer reach their destinations. Sunil goes through a number of steps and assumptions to derive an expression for DEP as function of ρ as well as an expression for ρ_{max} . The resulting equations are given by Eq. 2-14 and Eq. 2-15:

$$DEP = \frac{\rho}{\frac{2t_c(T_{tot}\bar{V} + d_{nr})}{pd_{cdr}T_{tot}A} - \rho} \quad (2-14)$$

$$\rho_{max} = \frac{2t_c(T_{tot}\bar{V} + d_{nr})}{pd_{cdr}T_{tot}A} \quad (2-15)$$

Here, t_c is the average time required to solve a conflict, T_{tot} is the analysis time interval, $\bar{V}$ is the average aircraft ground speed, d_{nr} is the average flight distance without CR, p is the conflict probability, d_{cdr} is the extra distance flown per conflict and, A is the area of the airspace. All parameter values are assumed known except for d_{cdr} , which is to be determined by using a least square approach to fit Eq. 2-14 to data resulting from simulation.

2-10 Conclusions

Based on the literature presented in the preceding sections the following conclusions can be drawn that could influence design decisions for the experiment:

- Corridors between both moving and non-moving airspace restrictions are relevant to commercial as well as UAS traffic.
- ADS-B messages can be received with virtually no loss up to around 100 NM range.
- The SSD method for conflict resolution was found to be less effective than the MVP algorithm in unconstrained airspace and does not guarantee solutions in constrained airspace.
- The leader-following method seems to have the best results with the follow-through module off in less constrained airspace and with the follow-through module on in more constrained airspace. However, these results are difficult to interpret due to the metrics used in the previous experiment.
- The Swarming Augmented MVP method performs worse than the regular MVP algorithm in unconstrained airspace but it is not known what the effect is in constrained airspace.
- Implementing aircraft-to-area conflict resolution will be easier for non-moving areas than for moving areas due to the different relative origins of collision cones and velocity obstacles.
- The results from the Metropolis project as presented in Section 2-8 and explained using the conflict rate model presented suggest that layered airspace structures are an effective method to reduce conflict rates by reducing relative velocities and the number of potential conflict pairs through limiting allowable heading ranges based on altitude.
- The CAMDA model provides an objective way to make comparisons between different SSEP methods and airspace designs. If the assumptions made in the model are valid for experiments proposed in this project then it could be a good candidate for use in comparing the proposed separation methods.

Chapter 3

Methodology

In the previous chapters an introduction to the general problem and an overview of relevant literature was presented. In this chapter the research scope is defined, the simulation environment is introduced, and a methodology is presented.

3-1 Research scope and assumptions

In the literature review presented in Chapter 2 it was seen that the presence of airspace obstacles is relevant in many different situations and for various types of air traffic. In this section the scope of the research project is narrowed through a number of assumptions.

Assumption 1 Only conventional commercial air traffic in the en-route phase is considered.

Although the research is relevant to Visual Flight Rules (VFR) traffic as well as UAS traffic in urban environments (as discussed in Section 2-1) only conventional air traffic in the en-route phase is studied. The choice for the en-route phase is because in terminal environments near airports other factors such as runway capacity can become a complicating factor and make the experiment results less applicable to real life situations.

Assumption 2 No centralized ATC guidance will be present and all aircraft will be responsible for self separating.

This assumption is closely tied to the research goal which is all about airborne SSEP. Instead of having ATC that controls aircraft based on a complete centralized overview of the airspace this research assumes that all aircraft will be exchanging relevant information via ADS-B.

Assumption 3 Perfect exchange of information via ADS-B communication is possible up to a maximum range of 100 NM.

This assumption aims to provide realistic data exchange limitations as they could be encountered in real life situations without introducing inaccuracies that complicate the evaluation of the separation method's performance. In Section 2-3 it was seen that ADS-B messages can be lost due to range effects over long distances and interference effects in busy airspace. Based on the findings in this section it is assumed that perfect reception with zero latency is possible and the maximum range for transmissions is 100 NM.

Assumption 4 All coordination between aircraft will be implicit.

The only traffic information that is available to aircraft is the data received via ADS-B and they use only this data to determine if any maneuvers have to be performed based on the separation algorithm. There will not be any explicit communication on actions taken to avoid or resolve conflicts.

Assumption 5 The CD methods for both aircraft-to-aircraft and aircraft-to-area will not consider intent.

The detection of conflicts will be based solely on a linear extrapolation of aircraft's current state position and velocity. This means that in some maneuvering situations conflicts can be detected that would not result in intrusions but still require additional action based on the separation algorithm rules.

Assumption 6 All aircraft in the experiment will fly at a single flight level and in the same direction through the corridors.

Based on the conclusions of the Metropolis project regarding airspace design in Section 2-8 it is assumed that aircraft in corridors will be implicitly separated in different layers based on their flight direction. This means that aircraft will not encounter traffic in opposite direction because such traffic would fly at a different level and is not simulated in the experiment.

Assumption 7 All CP and CR maneuvers are limited to the horizontal plane.

This assumption is closely related to Assumption 6 because vertical maneuvering out of a given level might generate conflicts with aircraft flying in opposite directions and according to Eq. 2-11 this would increase the conflict rate due to the increased relative velocity effect.

Assumption 8 All information regarding airspace restrictions is available to all aircraft and their routes are planned around these restrictions.

This assumes that at the moment an aircraft is created in the simulation it has complete knowledge of any and all airspace restrictions and is able to plan its route such that it avoids those restrictions.

Assumption 9 All aircraft will behave nominally at all times.

This assumption assures that no equipment failures or emergency situations will occur and all aircraft will always maneuver as dictated by the separation algorithms.

Assumption 10 Flat Earth approximations will be used for all conflict-related geometry calculations.

Due to the limited distances involved in the detection of both aircraft-to-aircraft conflicts and aircraft-to-area conflicts the errors due to the flat Earth approximation remain small.

3-2 The BlueSky simulation environment

The BlueSky simulation environment is an open source ATM simulator that is under continuous development at Delft University of Technology (DUT) [12]. It is written in the Python programming language and aims to provide a base platform that researchers can use to perform experiments. As such, it is highly customizable and users can extend the simulator with their own features.

BlueSky has a modular structure in which the different modules perform various tasks. For the user the program normally consists of a Graphical User Interface (GUI) that allows interaction with the simulator through a radar screen, a set of controls, and a command line interface. However, it can also be configured for use from the operating system command line without showing a GUI. The simulator uses open data for its navigation database and is compatible with multiple aircraft performance models. For this experiment the OpenAP performance model was used.

A number of existing algorithms, such as the MVP and SSD CR methods, have already been implemented in BlueSky and can be reused or extended in new experiments. The simulator offers the flexibility to perform both small and large scale traffic simulations to study the effects of these algorithms in varying conditions.

3-3 Research setup

In this section the details of the research setup are discussed. Firstly, the airspace scenario in which the experiments will take place is chosen. Secondly, a discussion on the avoidance methods for both static and moving airspace restrictions is presented. Then, several sets of steering rules that can be added to the MVP algorithm are given. Finally, these elements are integrated into a modular hierarchy with which the experiments in the next chapter will be performed.

3-3-1 Airspace scenario selection

The findings of the Metropolis project with regards to the effect of airspace structure on conflict rates and the resulting conflict rate model were discussed in Section 2-8. Based on those findings three different airspace concepts were considered for this research. However, since this research focuses on the effects of steering methods, only one airspace concept can be used because otherwise the project would become too complex.

General geometry

The general airspace geometry that will be used in the experiments is shown in Figure 3-1.

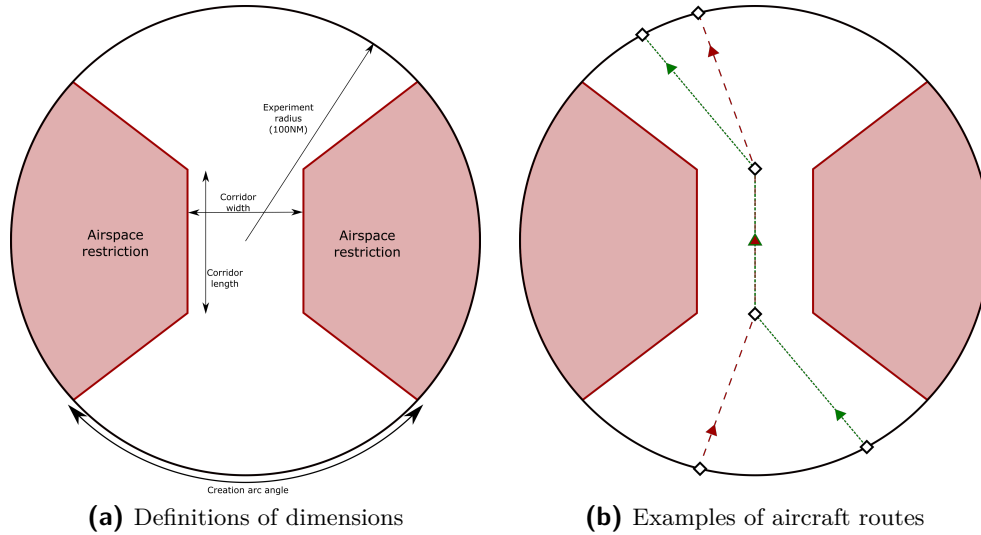


Figure 3-1: Generalized experiment area.

The experiment area is defined as a circular area with a radius of 100 nautical miles. Located inside this area are two airspace restrictions drawn in red. These areas are separated from each other by a corridor which is centered in the midpoint of the experiment area and forms the only connection between the region in the bottom and the region in the top of the experiment area. Traffic is only allowed to enter and exit the experiment area via the outer border of these regions. The size of the corridor is defined by its width and its length as shown in the figure. The shape of the regions is defined by the size of the corridor and both the arc which are always equal in length.

Proposed concepts

The following airspace concepts were considered for use in the experiments:

- **Full mix concept:** Aircraft can fly through the corridor in both directions at any altitude. Conflicts between aircraft can in principle occur at any point and in any 3D geometry.
- **Hybrid concept:** Aircraft can fly at their preferred altitude until they get near the corridor. They then have to climb or descend to cross the corridor at specific altitudes depending on their flight direction. Inside the corridor aircraft can not have head-on conflicts, but in the zones just outside the corridor there is a high potential for head on conflicts between climbing and descending aircraft.
- **Layers concept:** Aircraft are split into two groups based on the direction of flight and always fly at specific cruising altitudes depending on their flight direction. This means that conflicts can only occur inside a layer with aircraft at the same altitude and flying in the same general direction.

A visualization of these concepts is shown in Figure 3-2:

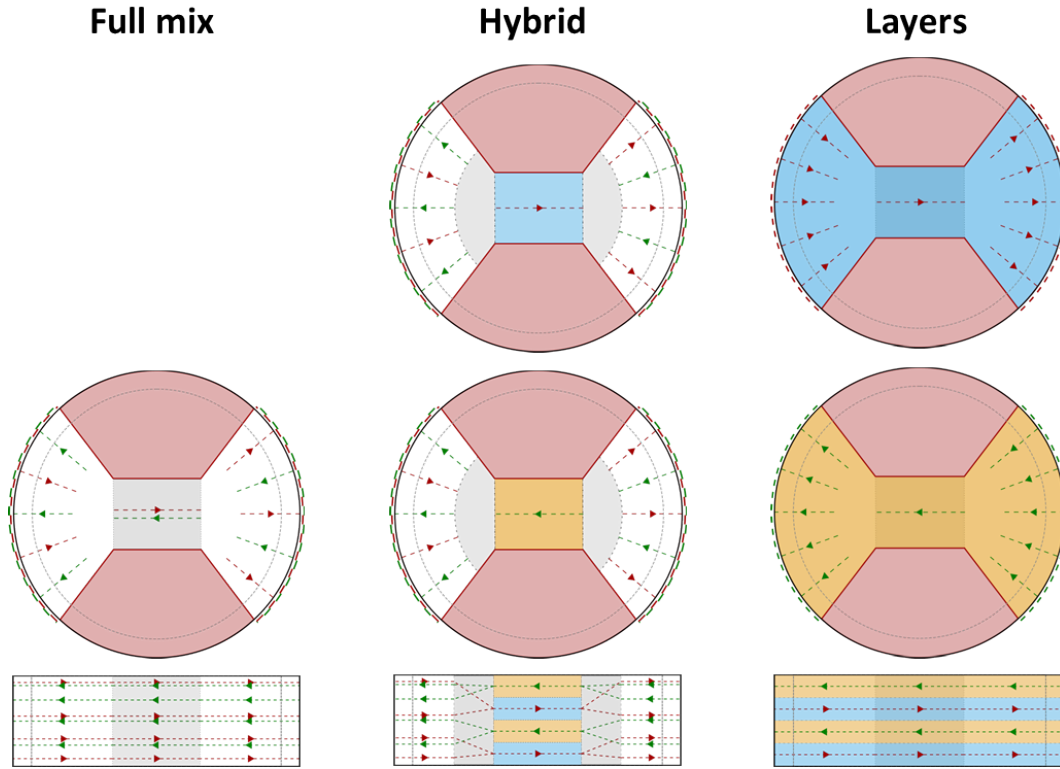


Figure 3-2: The three airspace concepts based on the Metropolis findings.

Selected concept

The concept that is selected for use in the experiments is the ‘Layers’ concept. This concept allows for the full isolation of a single layer so that the separation methods can be tested without interaction effects between aircraft at different altitudes. However, this also means that the vertical dimension can no longer be used to solve conflicts.

3-3-2 Area avoidance method

Area avoidance is a central topic because in this project aircraft will need to avoid the restricted areas. As was discussed in Section 2-5 different implementations would be required for the avoidance of static and dynamic areas restrictions.

Avoiding static airspace restrictions

Non-moving RAAs such as SUAs, controlled airspaces, and obstacles can be modeled as simple non-moving geographic polygons. As discussed in Section 2-5 a simple CC approach can be used to enable aircraft to avoid these areas. The details of the actual implementation for this method are discussed below.

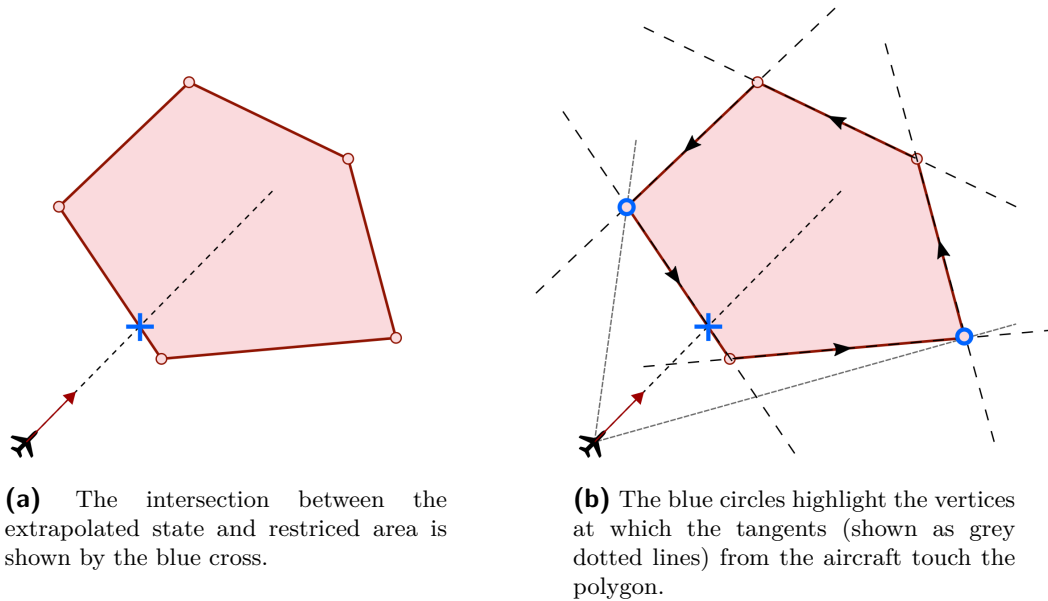


Figure 3-3: Example of an aircraft that is in conflict with an airspace restriction.

The for a given aircraft-area combination the conflict detection and resolution algorithm consists of the following steps:

- Linearly extrapolate the aircraft state up to its look-ahead time. If the line piece between this future position and the current aircraft position intersects the polygon then there is a conflict. Otherwise there is none and the next steps must be skipped.
- Find the vertices at which the tangent lines from the aircraft touch the polygon using the ‘Tangents point to polygon’ method described by Sunday [44].
- Calculate the course to these points and add a small margin in the direction away from the polygon to account for aircraft maneuvering.
- Turn to one of the two courses, depending on which one is closest to the planned route.

Avoiding dynamic airspace restrictions

Dynamic RAAs such as WHAs are more difficult to avoid than the static RAAs as was discussed in Section 2-5. Due to the fact that relative velocities between aircraft and area come into play in such cases, the method that is given for a static restrictions can therefore not be used on a moving restriction. Further details will not be discussed here, as the implementation details are considered out of scope for this research project.

3-3-3 Steering rule hierarchy

To create new separation methods by combining multiple steering rules a hierarchy is defined. The hierarchy that will be used in the experiments is shown in Figure 3-4.

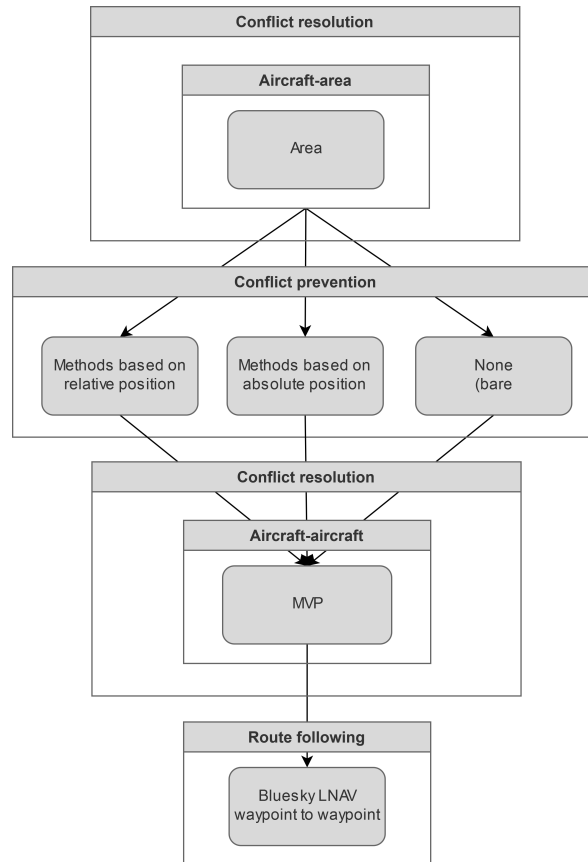


Figure 3-4: Steering rule hierarchy split into CR, CP and route following categories.

The aircraft-area conflict resolution rules are located at the top of the hierarchy because aircraft should never enter the airspace restrictions. This means that an area resolution maneuver trumps all other rules and must always be followed until the conflict is resolved. One level lower in the hierarchy are the conflict prevention methods. These are added ‘on top of’ the MVP method and as such must be able to override its resolution maneuvers. If these extra rules are not commanding a maneuver then the aircraft will simply either follow the MVP resolution in case of a conflict, or follow the flight plan route using the Lateral Navigation (LNAV) functionality in BlueSky.

Experiment proposal

Based on the method discussed in the previous chapter an experiment is proposed and its details are explained in this chapter. An overview of control variables is given in Section 4-1. The independent variables are introduced in Section 4-2. Following this, the dependent variables are discussed in Section 4-3. A two-phase experiment design is proposed in Section 4-4.

4-1 Control variables

This section gives a brief overview of the control variables in the experiment as well as the motivation behind their usage.

Traffic mix

An equal split between four different aircraft types will be used in the traffic mix to approximate the real world traffic scenario in which aircraft fly at different cruising speeds. The speed of each aircraft is randomly selected using a normal distribution with the average speed of the respective aircraft type and a standard deviation of 5 knots. The aircraft types and average Indicated Air Speed (IAS) that are used are shown in Table 4-1.

Table 4-1: Aircraft types, average speeds and percentages of traffic as used in all experiments.

Type	Average IAS	Traffic percentage
A320	258 knots	25 %
B738	260 knots	25 %
A333	273 knots	25 %
B744	284 knots	25 %

Experiment area

All experiments will be performed in the same circular area with a 100 nautical mile radius shown in Figure 3-1. The center of the area will be located at 0 degrees latitude and 0 degrees longitude. This choice was made to limit the complexity of the experiment area implementation in BlueSky. However, it does mean that the variation of corridor parameters (as described in Section 4-2-4) influences both the maneuvering space available to aircraft as well as travel time from the area edge to the start of the corridor.

4-2 Independent variables

Various factors affect the performance of SSEP methods in the experiment. This section introduces those parameters that are of interest in this research project.

4-2-1 Additional steering rules

The first and most important parameter in this study is the separation algorithm that is used to shape the traffic flow through the corridor. In line with the research question posed in the introduction of this report the effects of two types of additional steering rules are studied: those that depend on relative aircraft position and those that depend on absolute aircraft position.

Due to the nature of emergent behavior in distributed SSEP methods and the resulting "black-box-like" system complexity the performance of steering rules can only be determined experimentally. For this reason only the general categories are given here and specific implementations will be introduced in Section 4-4 where the experiment design is discussed.

Steering rules based on relative aircraft position

- Leader-following
- Leader-following with Follow-Through
- Swarming

Steering rules based on absolute aircraft position

- Course-limiting geovector
- Speed-limiting geovector
- Course and speed-limiting geovector

4-2-2 Traffic level

The traffic levels in this experiment is defined as the number of aircraft per unit of airspace area. Sunil et al reported an average traffic density of 32 aircraft per 10,000 NM² in the airspace above 18,000 feet over The Netherlands in 2018 [42]. For the circle with a radius of 100 nautical miles this would result in an average presence of 100 aircraft in the experiment area.

Based on experimental testing an average aircraft in this experiment takes 25.7 minutes to travel between its entrance and exit points without conflict resolution. This means that a traffic rate of approximately 235 aircraft per hour would need to be simulated to reflect the number of movements reported by Sunil. However, that reported figure encompasses *all* traffic above 18,000 feet, including aircraft climbing from and descending to airports whereas this experiment focuses only on cruising traffic at a single altitude layer. This means that lower traffic levels can be used to still give a meaningful result. The actual traffic levels used in the experiment are given in Table 4-2.

Table 4-2: Traffic levels used in the experiment with the approximate number of aircraft simulated per hour and approximate traffic density.

Level	ac/hour	Approximate density
LOW	50	7 ac/10,000 NM ²
MID	100	13 ac/10,000 NM ²
HIGH	150	20 ac/10,000 NM ²

4-2-3 Aircraft-to-area conflict look-ahead time

The area avoidance method used in the experiment is described in section 3-3-2. In this method the look-ahead time can be varied to change at what distance from a detected conflict aircraft maneuvers will be limited by area avoidance rules. Five different settings will be tested as shown in Table 4-3. The 60 seconds setting is approximately the minimum necessary to allow aircraft flying perpendicular to a restricted area to execute a turn without entering the area when turning.

Table 4-3: Aircraft-to-area conflict look-ahead time levels.

Level	Value
A	60 seconds
B	120 seconds
C	180 seconds
D	240 seconds
E	300 seconds

4-2-4 Airspace geometry

There are three parameters related to the airspace geometry that can be varied: the corridor width, corridor length, and the angle of the arc on which traffic can enter the experiment area.

The corridor width is of interest because due to the minimum required separation distance between aircraft it forms a limit to the maximum amount of aircraft that can enter the corridor simultaneously. Five different levels of this parameter will be tested as shown in Table 4-4.

The corridor length is of interest because it determines the space available to solve aircraft-to-aircraft conflicts before these conflict resolutions result in aircraft-to-area conflicts. Four different levels of this parameter will be tested as shown in Table 4-4.

The arc angle is of interest because it influences the relative heading angles that aircraft have with respect to each other when approaching the beginning of the corridor. Four different levels of this parameter will be tested as shown in Table 4-4.

Table 4-4: Levels and corresponding values for airspace geometry parameters.

Parameter	Level	Value
Corridor width	A	10 NM
	B	20 NM
	C	30 NM
	D	40 NM
	E	50 NM
Corridor length	A	0 NM
	B	20 NM
	C	40 NM
	D	60 NM
Arc angle	A	70 °
	B	90 °
	C	110 °
	D	130 °

4-3 Dependent Variables

This section describes the metrics and variables that will be used to assess the performance of the methods tested in the experiment. Conforming with present-day literature the metrics are split into the categories safety, efficiency, and stability.

Safety

The safety metrics give an indication of the ability of a separation method to keep aircraft at a safe distance from each other. The following metrics will be used in this experiment:

- The **number of conflicts** n_{conf} indicates the number of situations with the potential to result in a LoS.
- The **time to resolve a conflict** t_{conf} measures the time between conflict detection and the first moment where the aircraft are no longer in conflict. Any further time spent in the resolution maneuver, such as waiting until t_{cpa} has passed and route recovery, is not counted in this metric.
- The **number of Losses of Separation** n_{LoS} measures the number of situations in which the minimum separation distance is violated.
- The **intrusion prevention rate** IPR is a measure for the amount of conflict situations that are resolved before they result in a LoS [39]. It is defined in Eq. 4-1:

$$IPR = \frac{n_{conf} - n_{LoS}}{n_{conf}} \quad (4-1)$$

If the separation method is able to resolve all conflicts before they turn into LoS events then the IPR equals one. If all conflicts result in a LoS then it equals zero.

- The **LoS severity** LoS_{sev} is a measure for the minimum distance between aircraft during a LoS event [39]. This metric is defined as given in Eq. 4-2:

$$LoS_{sev} = \frac{R_{min} - d_{cpa}}{R_{min}} \quad (4-2)$$

Here R_{min} is the minimum separation distance and d_{cpa} is the distance between aircraft at the closest point of approach during a LoS situation.

- The **number of airspace intrusions** n_{int} indicates the ability of the separation algorithm to ensure that aircraft do not enter restricted areas.

Ideally, separation methods should have low conflict rates with zero losses of separation and zero airspace intrusions.

Efficiency

The efficiency metrics are a more economics and environment centered approach to evaluating the performance of separation methods. The following metrics will be used in this experiment:

- The **amount of work performed** W is a measure that gives an indication of fuel use. This metric can be calculated by integrating the thrust vector $\mathbf{T}$ along the flight path $\mathbf{s}$ using Eq. 4-3:

$$W = \int_{path} \mathbf{T} \cdot d\mathbf{s} \quad (4-3)$$

The lower the amount of work done, the less fuel an aircraft has used during its flight.

- The **route efficiency** η_{route} gives an indication of the actual distance traveled d_{actual} by aircraft with respect to their planned route distance d_{route} . A high route efficiency means that aircraft had little deviation from their planned route. The metric can be calculated using Eq. 4-4:

$$\eta_{route} = \frac{d_{route}}{d_{actual}} \quad (4-4)$$

Stability

Conflict resolution methods aim to resolve conflicts when they are detected but through maneuvering to do so they can also generate new conflicts that would not have existed otherwise. The tendency of these algorithms to either create or reduce these new conflicts is referred to as ‘stability’. This can be measured through the DEP [43], as given in Eq. 4-5:

$$DEP = \frac{n_{conf}^{ON}}{n_{conf}^{OFF}} - 1 \quad (4-5)$$

Here n_{conf}^{OFF} is the number of conflict pairs observed with CR switched off and n_{conf}^{ON} is the number of conflict pairs observed with CR switched on. The lower the DEP the fewer new conflicts a method generates and the higher its stability.

Capacity

The metrics listed earlier in this section all help provide a partial insight into the performance of the SSEP methods. However these metrics only give an indication at a specific level and experiment geometry. The CAMDA method introduced in Section 2-9 will be used to obtain a semi-empirical estimate of the maximum theoretical traffic capacity ρ_{max} . This metric enables performance comparison across different scenarios and requires only a relatively limited number of simulation runs.

Summary of metrics

A brief summary of the metrics discussed in the previous three sections is given in Table 4-5:

Table 4-5: Summary of the safety, efficiency, stability, and capacity metrics.

Category	Symbol	Description
Safety	n_{conf}	Number of conflicts detected
	t_{conf}	Time to resolve a conflict
	n_{LoS}	Number of Losses of Separation
	IPR	Intrusion Prevention Rate
	LoS_{sev}	Loss of Separation severity
	n_{int}	Number of airspace intrusions
Efficiency	W	Amount of work performed
	η_{route}	Route efficiency
Stability	DEP	Domino Effect Parameter
Capacity	ρ_{max}	CAMDA theoretical maximum capacity

4-4 Experiment design

Following the research questions posed in Section 1-1 and the proposed methodology discussed in Section 3-3 an experiment is designed. To mirror the structure of the research questions the experiment is split into two phases. First is an exploratory phase in which the individual effects of several geometry parameters and existing SSEP methods are studied in small-scale simulations. The results of the first phase are used to design a number of new SSEP methods that will hopefully have better performance. Then in the second phase these new methods are tested in a simplified experiment matrix with a larger number of simulation runs and higher traffic numbers.

4-4-1 Experiment Phase I

In the first experiment phase the aim is to explore the effects of various parameters on the performance of the separation methods. The following independent variables will be used:

- Traffic level
- Corridor width
- Corridor length
- Arc angle
- Aircraft-area conflict look-ahead time
- SSEP methods
 - CR OFF
 - MVP only
 - Leader-Following
 - Leader-Following with follow-through maneuvering
 - Swarming
 - Geovector in corridor with speed restriction only
 - Geovector in corridor with course restriction only
 - Geovector in corridor with both speed and course restriction

4-4-2 Experiment Phase II

The second experiment phase uses a more limited experiment matrix with only two independent variables: the new steering rules and the traffic level. The findings of the first phase will be used to select a single airspace geometry and a fixed aircraft-to-airspace look-ahead time, meaning these will become control variables for this phase. Based on the performance and emerging patterns of the SSEP methods seen in Phase I a number of new or updated methods will be tested, with the hope that their performance is able to deliver better results than the MVP method.

Bibliography

- [1] ICAO, “Long-term traffic forecasts passengers and cargo,” Online, Jul. 2016. [Online]. Available: <https://www.icao.int/Meetings/aviationdataseminar/Documents/ICAO-Long-Term-Traffic-Forecasts-July-2016.pdf>
- [2] R. Schaufele, L. Ding, N. Miller, H. A. Barlett, M. Lukacs, J. Corning, D. Bhadra, and T. Marotta, “FAA Aerospace Forecast: Fiscal Years 2018–2038,” *Washington, DC*, 2018.
- [3] Anonymous, “Unmanned Aircraft System (UAS) Service Demand 2015-2035,” Volpe National Transportation Systems Center, Tech. Rep., Sep. 2013.
- [4] “European ATM master plan,” in *Technical Report*. SESAR Joint Undertaking, 2012.
- [5] “The Future of the NAS,” Federal Aviation Administration, Washington, DC, June 2016. [Online]. Available: <https://www.faa.gov/nextgen/media/futureofthenas.pdf>
- [6] RTCA, “Final Report of RTCA Task Force 3 Free Flight Implementation,” RTCA, Inc., Washington D.C., Tech. Rep., Oct. 1995.
- [7] J. K. Kuchar and L. C. Yang, “A review of conflict detection and resolution modeling methods,” *IEEE Transactions on intelligent transportation systems*, vol. 1, no. 4, pp. 179–189, 2000.
- [8] J. Hoekstra, R. van Gent, and R. Ruigrok, “Conceptual design of free flight with airborne separation assurance,” in *Guidance, Navigation, and Control Conference and Exhibit*. Reston, Virginia: American Institute of Aeronautics and Astronautics, aug 1998, pp. 807–817.
- [9] J. Maas, E. Sunil, J. Ellerbroek, and J. Hoekstra, “The effect of swarming on a voltage potential-based conflict resolution algorithm,” in *7th International Conference on Research in Air Transportation*, 2016.
- [10] A. Kieskamp, “Reducing Complexity in Self-Separated Air Traffic by Alignment and Cohesion,” Master’s thesis, Delft University of Technology, Delft, The Netherlands, Mar. 2009.

- [11] J. M. Hoekstra, J. Ellerbroek, E. Sunil, and J. Maas, "Geovectoring : Reducing Traffic Complexity to Increase the Capacity of UAV airspace," in *8th International Conference on Research in Air Transportation (ICRAT 2018)*, Castelldefels, Spain, 2018.
- [12] J. M. Hoekstra and J. Ellerbroek, "BlueSky ATC Simulator Project: an Open Data and Open Source Approach," in *7th International Conference on Research in Air Transportation*, 2016.
- [13] J. M. Falker and J. K. Kuchar, "Analytical and Empirical Analysis of the Impacts of Restricting Airspace," *Air Traffic Management R&D Seminar*, pp. 3–7, 2001.
- [14] N. Doble, R. Hoffman, P. Lee, J. Mercer, B. Gore, N. Smith, and K. Lee, "Current Airspace Configuration Practices and Their Implications for Future Airspace Concepts," in *The 26th Congress of ICAS and 8th AIAA ATIO*, no. September. Reston, Virginia: American Institute of Aeronautics and Astronautics, sep 2008, pp. 1–13.
- [15] M. Weber, J. Evans, M. Wolfson, R. DeLaura, B. Moser, B. Martin, J. Welch, J. Andrews, and D. Bertsimas, "Improving Air Traffic Management During Thunderstorms," in *24th Digital Avionics Systems Conference*, vol. 1. IEEE, 2005, pp. 3.D.2–1–3.D.2–13.
- [16] S. Ramasamy, R. Sabatini, and A. Gardi, "A unified approach to separation assurance and Collision Avoidance for UAS operations and traffic management," in *2017 International Conference on Unmanned Aircraft Systems (ICUAS)*, no. Dm. IEEE, jun 2017, pp. 920–928.
- [17] J. M. Prete, "Aircraft routing in the presence of hazardous weather," Ph.D. dissertation, Stony Brook University, 2007.
- [18] "Helicopter Route Chart. New York," Federal Aviation Administration, Washington DC, Apr. 2016. [Online]. Available: http://aeronav.faa.gov/content/aeronav/heli_files/PDFs/New_York_Heli_11_P.pdf
- [19] H. C. Christmann and E. Johnson, "Modeling Urban Environments for Communication-Aware UAV Swarm Path Planning," in *AIAA Modeling and Simulation Technologies Conference*, no. August. Reston, Virginia: American Institute of Aeronautics and Astronautics, aug 2010.
- [20] ICAO, "Annex 11 to the Convention on International Civil Aviation." Montreal, Canada: International Civil Aviation Organization, 2001.
- [21] J. Ellerbroek, M. Visser, S. B. J. van Dam, M. Mulder, and M. M. van Paassen, "Design of an Airborne Three-Dimensional Separation Assistance Display," *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, vol. 41, no. 5, pp. 863–875, sep 2011.
- [22] Y. I. Jenie, E. J. Van Kampen, J. Ellerbroek, and J. M. Hoekstra, "Taxonomy of Conflict Detection and Resolution Approaches for Unmanned Aerial Vehicle in an Integrated Airspace," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 3, pp. 558–567, 2017.

- [23] M. Strohmeier, M. Schafer, V. Lenders, and I. Martinovic, "Realities and challenges of nextgen air traffic management: the case of ADS-B," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 111–118, may 2014.
- [24] T. Langejan, E. Sunil, J. Ellerbroek, and J. Hoekstra, "Effect of ADS-B Characteristics on Airborne Conflict Detection and Resolution," in *6th SESAR Innovation Days*, no. November, Delft, The Netherlands, 2016.
- [25] Anonymous, *Aeronautical Information Manual*, Federal Aviation Administration, Washington, DC, Oct. 2017.
- [26] M. Eby and W. Kelly, "Free flight separation assurance using distributed algorithms," in *1999 IEEE Aerospace Conference. Proceedings (Cat. No.99TH8403)*. IEEE, 1999, pp. 429–441 vol.2.
- [27] J. M. Hoekstra, R. C. J. Ruigrok, and R. Van Gent, "Free flight in a crowded airspace?" in *3rd USA/Europe Air Traffic Management Research and Development Seminar*, no. June, Napels, Italy, 2000.
- [28] J. Maas, "A Quantitative Comparison of Conflict Resolution Strategies for Free Flight," Master thesis, Delft University of Technology, 2015.
- [29] P. Fiorini and Z. Shiller, "Motion Planning in Dynamic Environments Using Velocity Obstacles," *The International Journal of Robotics Research*, vol. 17, no. 7, pp. 760–772, jul 1998.
- [30] J. van den Berg, Ming Lin, and D. Manocha, "Reciprocal Velocity Obstacles for real-time multi-agent navigation," in *2008 IEEE International Conference on Robotics and Automation*. IEEE, may 2008, pp. 1928–1935.
- [31] P. Hermes, M. Mulder, M. M. Van Paassen, J. H. L. Boering, and H. Huisman, "Solution-Space-Based Complexity Analysis of the Difficulty of Aircraft Merging Tasks," *Journal of Aircraft*, vol. 46, no. 6, pp. 1995–2015, nov 2009.
- [32] S. Balasooriyan, "Multi-aircraft Conflict Resolution using Velocity Obstacles," Master Thesis, Delft University of Technology, 2017.
- [33] ICAO, "Annex 2 to the Convention on International Civil Aviation - Rules of the Air," Montreal, Canada, 2005.
- [34] Y. I. Jenie, E.-J. V. Kampen, C. C. de Visser, J. Ellerbroek, and J. M. Hoekstra, "Selective Velocity Obstacle Method for Deconflicting Maneuvers Applied to Unmanned Aerial Vehicles," *Journal of Guidance, Control, and Dynamics*, vol. 38, no. 6, pp. 1140–1146, jun 2015.
- [35] A. Chakravarthy and D. Ghose, "Obstacle avoidance in a dynamic environment: a collision cone approach," *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, vol. 28, no. 5, pp. 562–574, 1998.
- [36] C. W. Reynolds, "Steering Behaviors For Autonomous Characters," *Game developers conference*, vol. 1999, pp. 763–782, dec 1999.

- [37] J. Maas, E. Sunil, J. Ellerbroek, and J. Hoekstra, "The Effect of Swarming on a Voltage Potential-Based Conflict Resolution Algorithm," in *7th International Conference on Research in Air Transportation (ICRAT 2016)*, Philadelphia, PA, 2016.
- [38] E. Sunil, J. Hoekstra, J. Ellerbroek, F. Bussink, D. Nieuwenhuisen, A. Vidosavljevic, and S. Kern, "Metropolis : Relating Airspace Structure and Capacity for Extreme Traffic Densities," in *11th USA/Europe Air Traffic Management Research and Development Seminar*, Lisbon, 2015.
- [39] E. Sunil, J. Ellerbroek, J. Hoekstra, A. Vidosavljevic, M. Arntzen, F. Bussink, and D. Nieuwenhuisen, "Analysis of Airspace Structure and Capacity for Decentralized Separation Using Fast-Time Simulations," *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 1, pp. 38–51, jan 2017.
- [40] J. M. Hoekstra, J. Maas, M. Tra, and S. E., "How Do Layered Airspace Design Parameters Affect Airspace Capacity and Safety ?" in *7th International Conference on Research in Air Transportation (ICRAT 2016)*, Philadelphia, PA, 2016.
- [41] M. Tra, E. Sunil, J. Ellerbroek, and J. Hoekstra, "Modeling the Intrinsic Safety of Unstructured and Layered Airspace Designs," in *12th USA/Europe Air Traffic Management Research and Development Seminar*, Seattle, WA, 2017.
- [42] E. Sunil, J. Ellerbroek, and J. M. Hoekstra, "CAMDA: Capacity Assessment Method for Decentralized Air Traffic Control," in *8th International Conference on Research in Air Transportation (ICRAT 2018)*, Castelldefels, Spain, 2018.
- [43] K. Bilimoria, K. Sheth, H. Lee, and S. Grabbe, "Performance evaluation of airborne separation assurance for free flight," in *18th Applied Aerodynamics Conference*, no. August. Reston, Virginia: American Institute of Aeronautics and Astronautics, aug 2000.
- [44] D. Sunday. (2012) Tangents to and between 2d polygons. Online. [Online]. Available: http://geomalgorithms.com/a15-_tangents.html