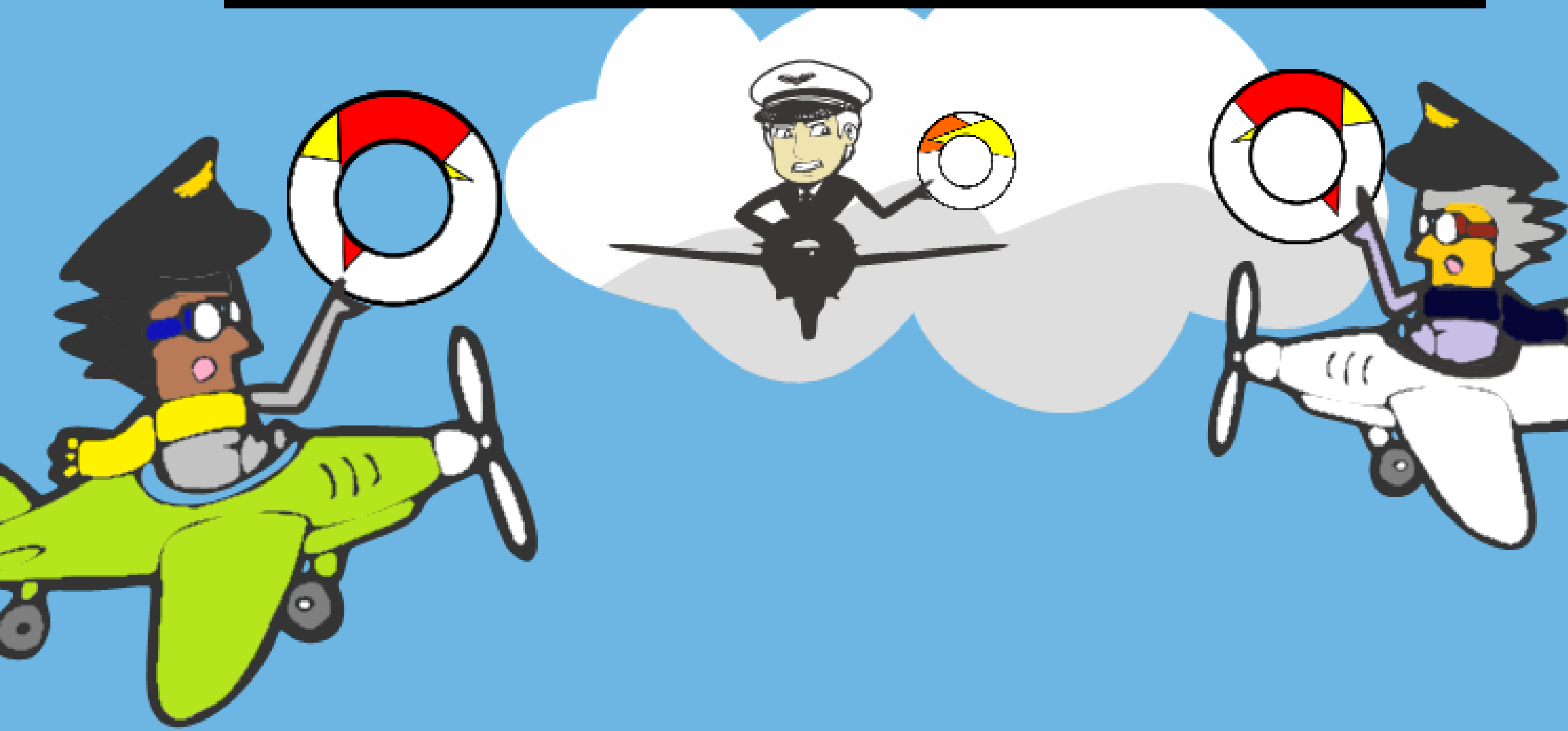
Faculty of Aerospace Engineering

Coordination in Multi-Actor Self-Separation in Complex Airspace Environments

A human-in-the-loop experiment using the Solution Space Diagram

S. Tegginamani Shiva Kumar

January 31, 2018



Delft University of Technology

Challenge the future

Coordination in Multi-Actor Self-Separation in Complex Airspace Environments

A human-in-the-loop experiment using the Solution Space Diagram

Master of Science Thesis

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

S. Tegginamani Shiva Kumar

January 31, 2018

Faculty of Aerospace Engineering · Delft University of Technology

Delft University of Technology

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 **"Coordination in Multi-Actor Self-Separation in Complex Airspace Environments"** by **S. Tegginamani Shiva Kumar** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: January 31, 2018

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Preface

Dear reader,

Thank you for your interest in this report. This is a report of my MSc Thesis titled "Coordination in Multi-Actor Self-Separation in Complex Airspace Environments". With this thesis, I got an opportunity to explore and contribute to Air Traffic Management research community to have a safer flight in the future when the sky is filled with more aircraft than ever in the history.

The presented thesis is the result of my work in the past one and a half years filled with emotions from enthusiasm and joy to those that came with the struggles of it. I came to Delft with high ambitions to set myself in the global stage of the aerospace industry. After three and a half years of my association with the Delft culture, I am proud of the many accomplishments which I hardly even thought of before I came here. During my time here, I learnt ice-skating, the most enjoyable sport I have tried so far. I intend to continue this hobby for as long as I can take it with me. Another achievement which I noticed a few months ago was the amount of biking that I had been doing since I moved about 10 km away from Delft. I calculated that I have biked at least 8500 km from July 2016 till now. Looking forward to add more to this number each year. The best part so far is undoubtedly the many friends who are always supporting me, arguing with me and giving me the best times of my life.

This thesis is a sum total result of the guidance and support received from my supervisors at the Control and Simulations section. Many thanks to Clark Borst, Joost Ellerbroek, Max Mulder and Rene van Paassen. My friends from the SIMONA 008 and my teammates from DARE have also provided valuable input in the numerous discussions. My friends from India and those from across the world supported me in the neediest of the times without whom I wouldn't be writing this piece of text today. Thank you very much. I thank the friends who helped me edit and improvise my final report. I want to thank Hans van der Laan, my mentor, who became a friend, and who is going to be a colleague, for the many discussions that have crossed our paths.

Special thanks to these close friends for just being there (in alphabetical order to avoid fights): Anouschka, BSK10 housemates, Dhruva, Franz, Kiran, Kodgi, Krishna, Marten, Monika (R.T.), Pranav, Priyanka, Rickert, Sagar, Shiva Kumar, Shreyas, Sumedh and Vinay.

Last but not the least, my parents. ....
....

I have no words that can express the strength, support, confidence and the resilient attitude that my parents have infused in me.

With many memories still fresh from my studies at the Faculty of Aerospace Engineering, I am very happy to move on to the next leg of my life.

Siddarth Tegginamani

January 2018

Delft, The Netherlands

Acronyms

d_{CPA}	Distance at Closest Point of Approach
t_{CPA}	Time to Closest Point of Approach
t_{LA}	Look Ahead Time
t_{LOS}	Time to Loss of Separation
ADS-B	Automatic Dependent Surveillance - Broadcast
ATC	Air Traffic Control
ATCO	ATC Officer / Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Services
CMATS	Civil Military ATM System
CPA	Closest Point of Approach
distributed ATM	distributed Air Traffic Management
EID	Ecological Interface Design
FAA	Federal Aviation Administration
FBZ	Forbidden Beam Zone
FBZ legs	Legs of the Forbidden Zone
FF	Free Flight Air Traffic Management
GPS	Global Positioning System
HITL	Human-in-the-loop
ICAO	International Civil Aviation Organization
LOA	Level of Automation
LOS	Loss of Separation
MLAT	Multilateration
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NextGen	Next Generation Air Transportation System

nmi	Nautical mile
PFD	Primary Flight Display
PZ	Protected Zone
RotA	Rules of the Air
SESAR	Single European Sky ATM Research
SESAR-JU	Single European Sky ATM Research Joint Undertaking
SSD	Solution Space Diagram
SWO	Shortest Way Out
TCAS	Traffic Collision Avoidance System

List of Symbols

Greek Symbols

χ	Heading angle or Track angle

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Report Structure

This graduation report is divided into two parts:

In **Part I**, a scientific paper is presented with the main findings of this research.

In **Part II**, the appendices to the scientific paper is presented. The appendices provide more insight and information on procedures employed in the scientific paper. Additional results that were not presented in the paper and the results of statistical analyses are also presented in this part

Part I

Master of Science Thesis Paper

Coordination in Multi-Actor Self-Separation in Complex Airspace Environments

Siddarth Tegginamani Shiva Kumar (Graduate Student)
Supervisors: dr.ir. Clark Borst (Assistant Professor), dr.ir. Joost Ellerbroek (Assistant Professor), dr.ir. Marinus (René) M. van Paassen (Associate Professor), dr.ir. Max Mulder (Full Professor)

***Abstract*—The Air Traffic Management research community expects that the responsibility of maintaining a minimum safe separation distance between aircraft will move from the ground-based Air Traffic Control, a centralized system, towards the flight deck, a decentralized system. Previous research on the decentralized, also known as distributed Air Traffic Management systems has shown promising results. However, aspects of coordination when more than two aircraft controlled by human operators are still to be explored. This paper presents an experimental research to study the coordination behavior of multiple actors using an ecological interface, known as the Solution Space Diagram (SSD), for the Conflict Detection & Resolution (CD&R) tasks. To judge the performance of humans, an automated conflict resolution algorithm, known as the Modified Voltage Potential (MVP), was used as the baseline.**

Several multi-aircraft scenarios were designed and simulated in a human-in-the-loop experiment. Results show that humans using the SSD display for the CD&R tasks operated safely for the designed scenarios. Compared to the resolutions of the MVP algorithm for the same scenarios, the humans depicted a safer and less efficient approach than the automated algorithm. For future research, attention was brought to aspects participant training in multi-actor experiments. The primary recommendation made was to explore the aspects of the efficiency of the human while using the SSD display by providing cues within the SSD.

***Index Terms*—Solution Space Diagram (SSD), Distributed Air Traffic Management, Free Flight, Human-in-the-loop experiment, Conflict Detection & Resolution (CD&R), Coordination in Multi-Aircraft Conflict Resolution, Coordination in Air Traffic Management**

I. Introduction

INCREASING air traffic over the past few decades has raised the concern towards the safety of air travel in the future [1], [2]. Researchers are exploring various methods in which the important factors of air travel such as the airspace safety, efficiency, and eco-friendliness can be increased [3]–[5]. The two main areas of research in the field of Air Traffic Management (ATM) are the centralized and decentralized ATM.

Previous research has identified valuable characteristics of the centralized and decentralized ATM systems [6]–[8]. In a centralized ATM system, the ground station has the sole responsibility of maintaining the safe separation between aircraft within the specified sector of the airspace. A centralized air traffic controller, a human or an automated system, moderates the aircraft trajectories to maintain the safe separation. In a decentralized ATM system, also known as the distributed ATM system, the responsibility of maintaining the safe separation between the aircraft is at the cockpit, with the pilots or an automation.

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Advanced and future technologies makes the distributed ATM system more feasible and reliable [7], [9]–[11]. Previous research has shown promising results for distributed ATM systems for computer simulations [8], [12], [13] and human-in-the-loop experiments [14]–[17]. Though the distributed ATM systems look promising, there are aspects of it that are still under research [18]–[21].

One concern is the coordination in conflict resolution. An aircraft pair is said to be in a conflict if it is expected to have a breach of the zone of the safe separation distance within a certain look-ahead time. Conflicts are resolved by changing the state of the aircraft. The manner in which the state is changed to resolve a conflict is determined by the rules of coordination (or coordination rules). In a distributed environment, the coordination in conflict resolution is essential for maintaining the safety of the airspace [22], [23]. The coordination rules define and mandate the action that needs to be taken by the involved aircraft depending on the conflict geometry.

There are several rules of coordination explored within the ATM research community for application in the distributed ATM environment [20], [24]–[26]. These rules of coordination, however, are defined and applied for aircraft pairs and are not explored in environments involving more than two aircraft. The consequence of the pairwise coordination rule is that it can present an ambiguous situation when more than two aircraft are involved in the conflict. For example, the resolution of a conflict between an aircraft pair might result in an opposing maneuver for the resolution of conflict for a third aircraft. Or, in some situations, it may as well give rise to a new conflict. Further, these rules of coordination only apply to aircraft which are on conflicting trajectories and are disregarded for aircraft which are not. So aircraft which are non-conflicting-yet-influencing are omitted till they become involved in a conflict. In multi-actor coordination, it is important to make a maneuver considering these effects. Otherwise, the resulting situation may present a new conflict or even an intrusion of the zone of safe separation.

With the increasing air traffic, it is imperative to have insights on the aspects of coordination in situations with more than two aircraft (from now on referred to as multi-aircraft situation). These insights will provide valuable information on whether distributed ATM systems can indeed be a safe and viable option for the future. Hence, an experimental research is proposed to explore these aspects in a human-in-the-loop experiment. Humans make unpredictable and unique decisions as opposed to computers. The analyses on the evolution of traffic situations and coordination between multiple human actors may provide interesting insights on the coordination in the multi-aircraft conflict resolution scenarios.

The Solution Space Diagram (SSD) will be used to assist pilots in the Conflict Detection and Resolution (CD&R) tasks. The SSD is an airborne self-separation display that is under research at the Delft University of Technology. It is an ecological interface that calculates and identifies the safe and unsafe maneuverable velocity spaces within a specified look-ahead time within the performance limits of a given aircraft [19], [20]). The SSD has been used in both the centralized and distributed ATM research [16], [19], [26]–[29]. It has also shown promising results in computer simulations and human-in-the-loop experiments [23]. However, it is unknown if it would perform sufficiently in assisting human pilots to navigate in airspace environments with multiple aircraft. Employing this tool for the present research will also provide insights on whether using the SSD in multi-actor distributed ATM environments is safe for the future. Additionally, using the SSD for this research would also give an opportunity to compare the performance of the SSD as opposed to an automated CD&R algorithm, giving useful insights for further development of the SSD. Hence, the main objective of the research will be framed as follows.

"To investigate the overall safety performance of the airspace and the emergent behavior of multiple pilots (>two) acting in complex air traffic environments, using the Solution Space Diagram for the Conflict Detection and Resolution tasks by conducting a human-in-the-loop experiment"

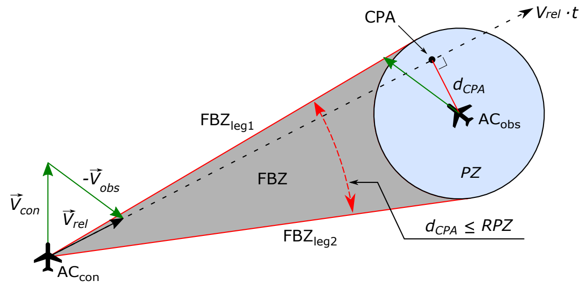
The Modified Voltage Potential (MVP) algorithm [30], [31], an automated CD&R method, will be used a baseline to judge the performance of the humans.

The structure of the paper is as follows. In Section II, a brief background on the construction of the SSD and the properties of the SSD will be presented. In Section III, several rules of coordination for conflict resolution will be explored. In Section IV, a new approach to classify multi-aircraft conflict scenarios will be proposed. Next, in Section V, the experiment design for the human-in-the-loop experiment and the simulation for automated algorithm will be described. The results will be presented in Section VI and the discussion of the results are done in Section VII. Finally, the conclusion is made in Section VIII.

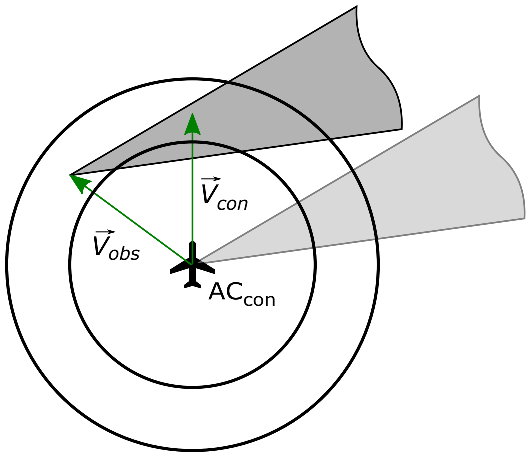
II. The Solution Space Diagram

A. Construction

The Solution Space Diagram can be constructed based on the concept of the velocity obstacles from robotics [32]. To construct an SSD for a given aircraft, the velocity obstacles are calculated in the absolute velocity space and then bounded within the performance (velocity) limits of the given aircraft. Figure 1 (a) shows the conflict geometry for an aircraft pair (the controlled and observed aircraft AC_{con} and AC_{obs}, respectively) and the velocity obstacle calculated in the relative velocity space for AC_{con}. PZ is Protected Zone, CPA is the Closest Point of Approach, RPZ is the Radius of the PZ and t is time. Figure 1 (b) shows the same situation transferred into the absolute velocity space, also including the performance limits of the AC_{con} as a pair of concentric circles.



(a) In the relative velocity space



(b) In the absolute velocity space, with velocity limits

Fig. 1. Conflict geometry and velocity obstacle for a pair of aircraft (adapted from [23])

Figure 2 shows the final form of the SSD which only shows the region within the velocity limits (for the detailed construction of the SSD, please refer to [23], [26], [28], [29]). The velocity obstacle in the SSD is referred as the Forbidden Beam Zone (FBZ). For the case presented in Figure 1, it is clearly a conflict since the velocity vector lies inside the FBZ. This conflict can be resolved by changing the $\vec{V}_{con}$ to any point outside the FBZ.

B. Properties of the Solution Space Diagram

The SSD intuitively presents information as safe and unsafe maneuverable velocity regions in the absolute velocity space of the given aircraft. In a situation with multiple aircraft, individual FBZ for each aircraft within a certain look-ahead time ($t_{look-ahead}$) can be grouped into a single SSD display. Further, the FBZ can be displayed in a distinguishable order

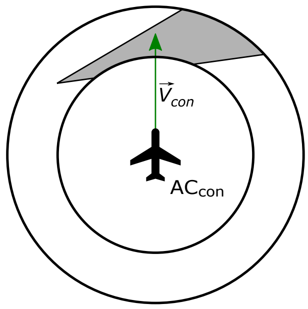
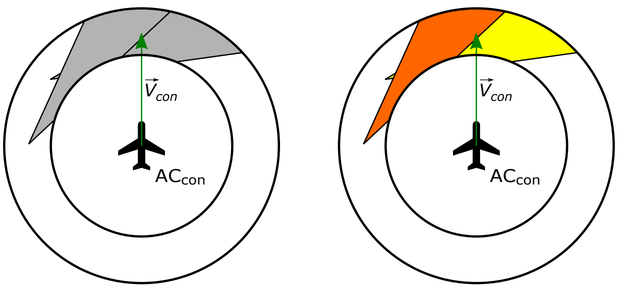


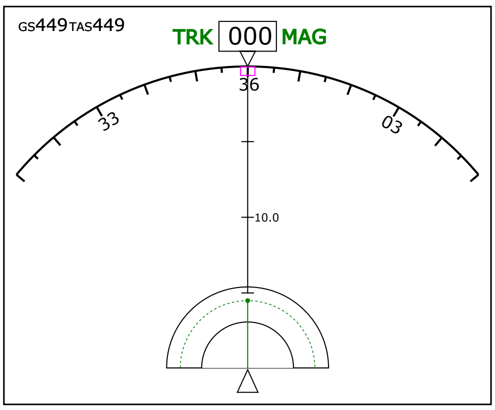
Fig. 2. The Solution Space Diagram as viewed from AC_{con} (adapted from [28])

that sets a priority based on the time to loss of separation (t_{LoS}). That is, the FBZ on the top indicates a conflict with the loss of separation (LoS) earlier than for the FBZ at the bottom (see Figure 3 (a)). The FBZ in the SSD can also be color-coded to provide further visual cues on the nature of the conflict. The color-coding is done based on the range (or bin) in which t_{LoS} for the particular FBZ falls in. Each category is color-coded to represent the level of urgency (see Figure 3 (b)). The coloring of the FBZ in the SSD display based on the t_{LoS} can be used to strategize the maneuvers for the resolution of conflicts.



(a) Stacking multiple conflicts based on the t_{LoS} (b) Color coding the FBZ based on the t_{LoS}

Fig. 3. Illustration of the properties of SSD

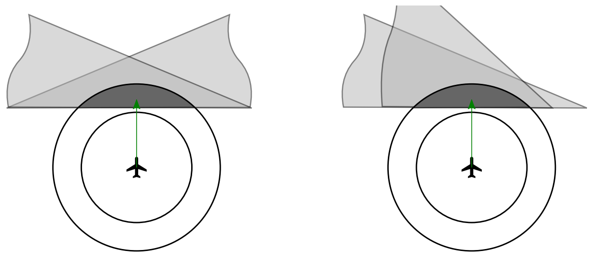


(a)

Fig. 4. SSD integrated in Navigation Display (adapted from [21])

It has been shown in previous research that the SSD display can be integrated with the Navigation Display (see Figure 4) of a cockpit to assist the pilots in CD&R in distributed environment [21].

A point to note while using the SSD is the ambiguity in cases when the observed aircraft's velocity ($\vec{V}_{obs}$) is beyond the maximum velocity limit of the controlled aircraft and only one of the FBZ legs is visible within the velocity limits of the AC_{con}. This leads to an ambiguity in the bearing of the observed aircraft since it can be on either side (Figure 5 (a)). Additionally, the geometry of the FBZ is also unknown (Figure 5 (b)).



(a) Ambiguity in the bearing of the intruder (b) Ambiguity in the geometry of the FBZ

Fig. 5. Ambiguities using the SSD display

In the context of this research, such situations can be avoided by making an assumption on the aircraft velocity limits. The assumption is to use the same velocity limits for all the aircraft involved. This results in the tip of the FBZ to always lie within the maximum velocity limit of the SSD, which in-turn provides information on the orientation of the observed aircraft.

III. Coordination in Conflict Resolution

A. *What is Coordination?*

A conflict resolution can either be a coordinated or an uncoordinated maneuver. A resolution is called coordinated if it ensures a safe separation when both aircraft simultaneously resolve the conflict. Otherwise it is an uncoordinated resolution. Further, there are two type of coordinated resolutions. A coordinated resolution is implicit when no explicit negotiation about the resolution maneuvers to be taken is required. On the other hand, it is explicit coordination if communication is needed on the type of the maneuver to be executed.

B. *The Rules of Coordinations*

The rules of coordination are defined for different situations of the air traffic. The rules based on Annex II from International Civil Aviation Organization (ICAO) [24] and based on the SSD will be explored. The rules of coordination based on the SSD are developed based on the nature of the FBZ that is seen on the SSD display. First, the coordination between two aircraft conflict is analyzed and then between multi-aircraft conflict.

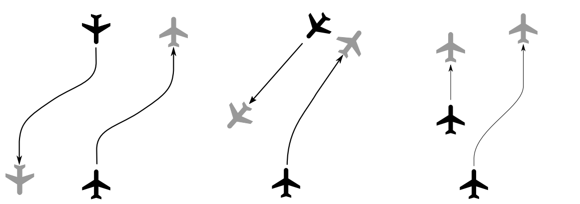
1) Rules of the Air: ICAO has laid out the *Rules of the Air* in Annex II [24]. Any aircraft flying over high seas in member countries must fly in compliance with the *Rules of the Air*. A summary of the coordination rules for the same type of aircraft is as follows:

Rule 1: The aircraft that has the right-of-way shall maintain its heading and speed.

Rule 2: When two aircraft at approximately the same flight level are approaching head-on or approximately so, and there is a danger of collision, each aircraft shall alter its heading to the right (see Figure 6 (a)).

Rule 3: When two aircraft at approximately the same level are on a converging track, the aircraft that has the other on its right shall give way (see Figure 6 (b)).

Rule 4: An aircraft that is being overtaken has the right-of-way and the overtaking aircraft shall keep out of the way of the other aircraft by altering its heading to the right (see Figure 6 (c)).



(a) (b) (c)

Fig. 6. Coordination rules according to the *Rules of the Air* (a) a Head-on approach (b) a converging track (c) an overtaking approach

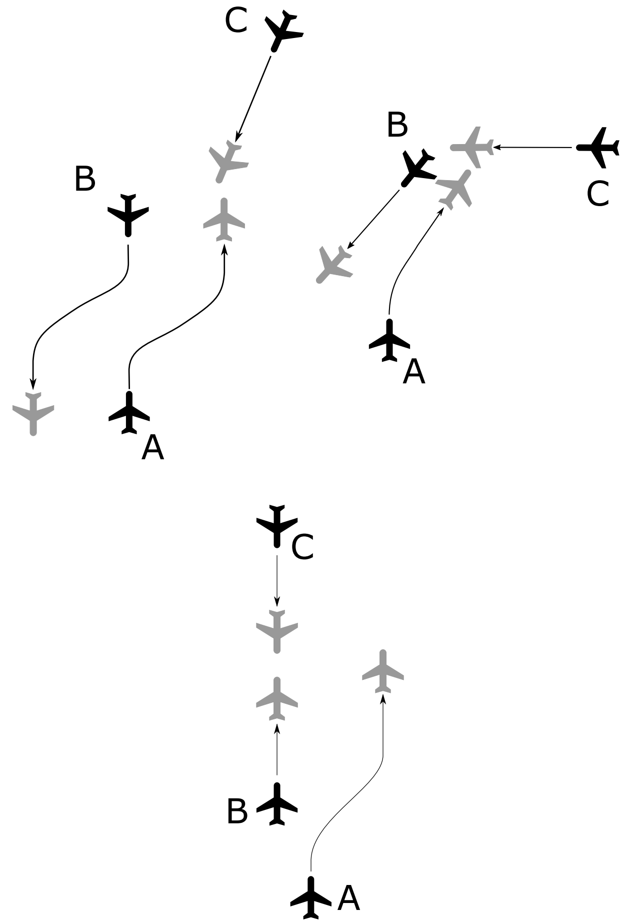
The *Rules of the Air* define the type of resolution maneuver to be executed for a pair of conflicting aircraft. From Figure 6, it is seen that the implicit coordination is possible for two aircraft conflict resolutions. Now consider a third aircraft as presented in Figure 7 (a). Aircraft A and B are on a head-on approach. The resolution according to the *Rules of the Air* for both A and B would be to alter their heading to the right. However, this makes aircraft A come into conflict with the third aircraft C. So the maneuver for the resolution of the first conflict results in a second conflict.

Similarly, for the converging track and the overtaking maneuver, a third aircraft creates an ambiguous situation leading to knock-on conflicts (Figures 7 (b) and (c)). The *Rules of the Air* fail to provide a resolution method that is safe and efficient in multi-aircraft scenario.

2) Using the SSD: Resolution Based on A Maneuver Preference: The SSD display presents the conflicts in such a way that several rules of coordination are developed based on the geometry of the forbidden beam zones. The rules explored are discussed below.

Coordination based on the maneuver preference: There are two aspects of the coordination based on the maneuver preference. The permitted resolution maneuvers for an aircraft in conflict are either a heading-change or a speed-change only [25].

Figures 8 (a) and (b) show the SSD resolution maneuvers for situations using the heading-change-only resolutions. Figures 8 (c) and (d) show the SSD resolution maneuvers for a similar scenario, but with the speed-change-only resolutions.



(a)

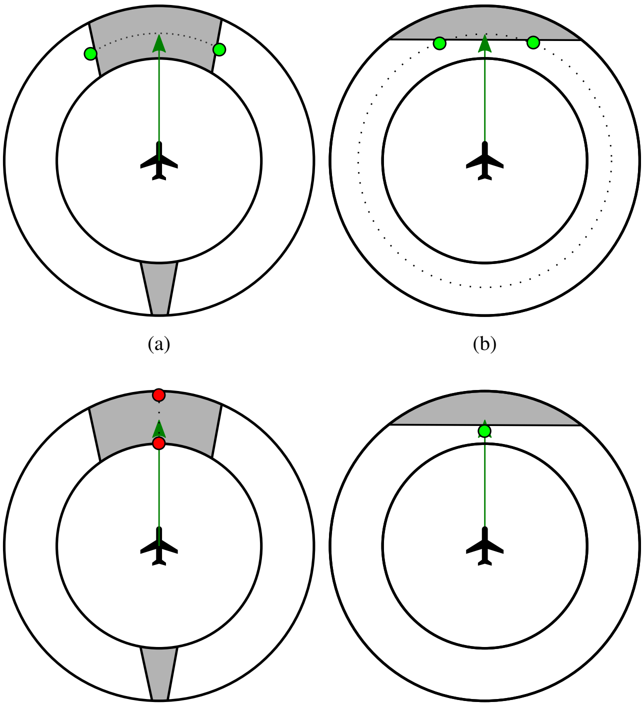
Fig. 7. Three aircraft scenario leading to the knock-on effect after resolving the first conflict: clockwise from top-left: head-on approach, converging track and overtaking approach

The SSD in Figures 8 show that the heading-change-only resolution ((a) and (b)) guarantees a resolution of conflict in two aircraft scenario, while speed-change-only resolution ((c) and (d)) fails in the head-on and over-taking maneuvers. There is also a failure case possible where the available speed is entirely covered with a FBZ.

Consider the multi-aircraft situation as shown in Figure 9. It is seen that the heading-change-only resolution rapidly declines in its performance. However, speed-change-only resolution is seen to be more efficient.

As seen for two aircraft conflicts, the speed-change-only resolution method is not reliable due to the limited free velocity space available for a conflict resolution. On the other hand, the heading-change-only resolution method leads to severe inefficiencies due to the knock-on effects in multi-aircraft scenarios. Therefore, neither the speed-change-only nor the heading-change-only resolution method can be the coordination rule in multi-aircraft conflict resolutions.

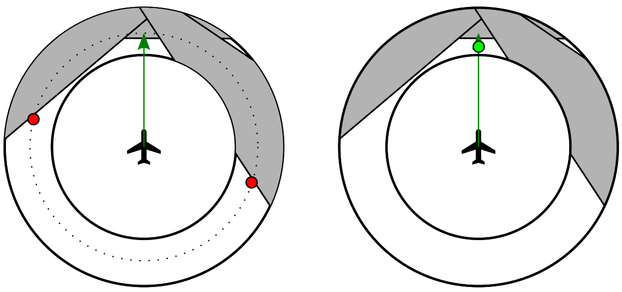
3) Using the SSD: Shortest-Way-Out Resolution: The Shortest-Way-Out (SWO) resolution is the resolution with



(a) (b)

(c) (d)

Fig. 8. The SSD for two aircraft conflict for a heading-change-only ((a) & (b)) and speed-change-only resolution ((c) & (d)).

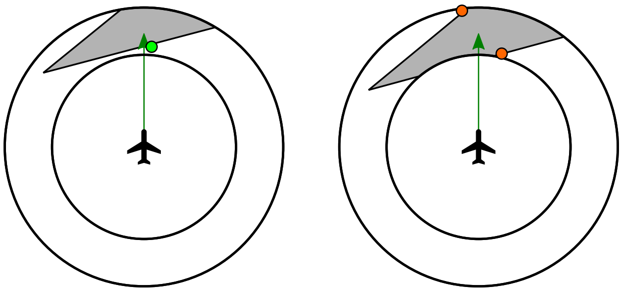


(a) Heading-only resolution (b) Speed-only resolution

Fig. 9. The SSD for three aircraft scenario

smallest vector change out of the FBZ of a conflict represented in the SSD. SWO results in the lowest path deviations in conflict resolutions [20], [26]. Geometrically, this is the perpendicular distance from the current velocity to the closest FBZ leg. Figure 10 (a) shows the SWO resolution point for two aircraft in conflict. The SWO resolution method is a combination of the heading change and the speed change maneuver.

It can also be seen that the drawbacks of the previous coordination methods are overcome in the SWO resolution method since there are alternatives, always available as a shortest way out of the conflict. The SWO resolution works better than previously mentioned coordination methods for two aircraft conflicts and always results in implicit coordination, however, with a case of exception that leads to ambiguity.



(a) SWO demonstration for two aircraft in conflict (b) SWO failure Case for two aircraft scenario

Fig. 10. The SWO resolution method

The exception is when the FBZ legs are nearly equidistant from the current velocity vector of the controlled aircraft (Figure 10 (b)). This creates an ambiguity in the type of maneuver to execute since there is no unique SWO maneuver. This is caused when the d_{CPA} of the conflict pair is close to 0 nmi. This exception shows that an implicit coordination using SWO method is not possible for all situations with two aircraft. In the context of this research, such situations can be avoided by making assumptions on the design of the conflict geometry such that the conflicts are designed with a d_{CPA} not close to 0 nmi.

Consider a three aircraft situation using the SWO method as shown in Figure 11. The case would result in the controlled aircraft to sway between the two conflicts since the SWO resolution of each conflict contradicts one another. This situation would eventually result in an intrusion. Hence, the SWO method fails for multi-aircraft conflicts.

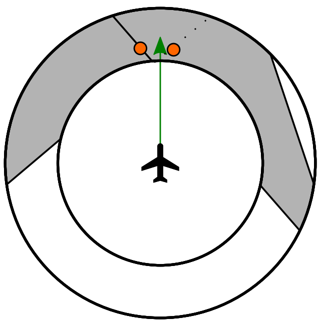


Fig. 11. Failure of the SWO method for three aircraft in conflict

4) Using the SSD: Maintain Safety: From the rules of coordination analyzed previously, it can be concluded that none of the rules discussed were capable of handling multi-aircraft situations. The knock-on effects in the resolution of multi-aircraft conflicts create an unpredictable situation. This makes coordination in multi-aircraft scenarios using a particular coordination rule a challenging task.

A different approach is needed to ensure safety in multi-aircraft scenarios. Rather than defining a particular resolution maneuver based on the conflict geometry, requiring that the safety be maintained by any suitable maneuver gives more flexibility in resolving a conflict depending on the traffic situation in the vicinity. This method gives more freedom to the controlling agent to prioritize the safety of the aircraft by using a combination of different resolution methods (a heading-only change, a speed-only change or a combination of both) to solve more than one conflict at a time. Although heading change maneuvers are desired more since they are more efficient in terms of flight performance, the availability of speed change maneuvers provide more flexibility in a dense environment. Previous research also shows that the conflict situations are most efficiently resolved by a speed change, a heading change, or a combination of both depending on the conflict geometry [19].

This approach also solves the ambiguity created in SWO coordination for three aircraft situation (Figure 11) by providing an option for a sequential resolution (solving conflicts one after the other) as well as a global resolution (solving all conflicts with a single maneuver).

It is important to note that this method does not necessarily result in an implicitly coordinated resolution in multi-aircraft conflicts. However, such maneuvers can be treated as part of the strategy to resolve multiple conflicts.

IV. Classification of Multi-Aircraft Conflicts

A. The need for classification

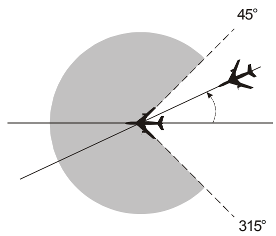
Before designing the traffic scenarios, a quantifiable way of differentiating different traffic situations for multi-aircraft conflicts is needed. It is essential to design the air traffic scenarios such that they can be differentiated to identify the conflicting aircraft and the aircraft that are not in conflict, but influence the situation around the time to loss of separation. The classification of air traffic conflicts will provide a basis to design and classify the complex airspace environments to be used in the experiment.

B. Existing Methods and Previous Research for Conflict Classification

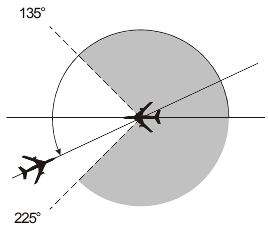
ICAO's criteria for air traffic classification for two aircraft, shown in Figure 12, depend on the relative bearing of the intruder [33]. The aircraft pair is said to be on the "same track" if the relative bearing is between $-45°$ and $+45°$, "reciprocal track" if the relative bearing is between $135°$ and $225°$, and "crossing track" for the remaining bearings. The ICAO's system of classification works well for the aircraft that are considered pairwise. However, for situations involving more than two aircraft, the ICAO system fails to provide the overall situational information.

Previous research to classify air traffic by obtaining a set of maneuvers to cover all possible conflict scenarios involving multiple agents in a decentralized ATM environment led to a complicated system [13]. Also it was defined only for special cases of the air traffic situations. It was too specific for the assumptions made in the research and may not necessarily reflect the reality in most cases. On the concluding note, the authors recognize that a proper classification for multi-aircraft conflict scenarios and maneuvers is a challenge.

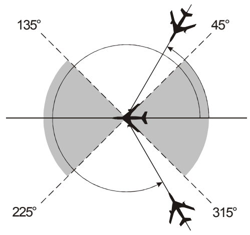
The importance of classification of air traffic conflicts for this research led to further exploration by trial and error method on the basis of these existing methods. After failing to come up with a classification system by modifying the existing system, an entirely new system for the multi-aircraft classification is explored.



(a) Same Track



(b) Reciprocal Track



(c) Crossing Track

Fig. 12. ICAO Conflict classification for two aircraft (adapted from [33])

C. Requirement Specification

The new classification system should be compatible with the situations involving multiple aircraft. It should be able to provide a general situational insight of all the aircraft in conflict and the aircraft on the verge of becoming a conflict due to a knock-on effect. It should be straightforward and concise to apply to a given scenario and classify it.

D. The New Approach: The C-I Classification System

The critical parameter that defines the criteria for the new classification is the number of aircraft in the given air traffic situation that fall into different categories. Three separate categories are defined: Conflicting Aircraft, Influence Aircraft, and Uninvolved Aircraft. The conflicting aircraft are those that are in conflict. the influence aircraft are those that are not conflicting aircraft but have the potential to be one or influence existing conflicts within the given look-ahead time. Uninvolved aircraft are those that are neither a conflicting nor an influencing aircraft.

The total number of aircraft in each category is a metric that classifies the air traffic situation. Since the presented research's focus is only on the aircraft involved in that conflicts and that aircraft that may have knock-on effects, the metric of uninvolved aircraft is discarded. The terms C_m and I_n represent the metrics for the conflict and influence aircraft, where m and n are the numbers of conflicting and influence aircraft respectively.

The notation C_mI_n represents a traffic scenario. A conflict only scenario is written as C_m, while a combination of conflict and influence scenario is written as C_mI_n (for example, see

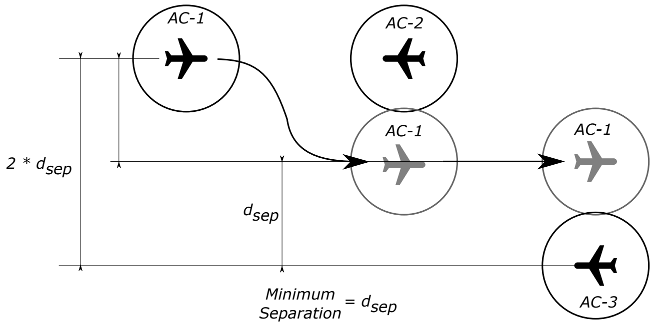
Figures 14 (a) and 15 (a)). This method also meets the requirements set earlier. The new classification system uses information on the number of conflicting aircraft and the influence aircraft in a given situation, and hence the name *Conflict-Influence Classification*, or in short, *C-I Classification* is given for this system.

It is important to note that the presented classification system is not a unique notation of a given scenario because the consideration of velocities and headings of individual aircraft are not accounted for in this approach. It is instead a representation of a case of the multi-aircraft traffic situation in a generalized manner, again meeting one of the requirements.

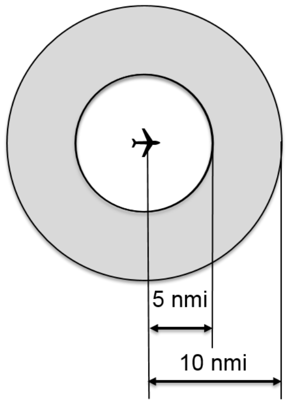
E. Identification of the Influence Aircraft

Any aircraft is called an influence aircraft if it has the potential of encountering a conflict as a knock-on effect. Influencing aircraft are those aircraft whose distance at the closest point of approach (d_{CPA}) with another aircraft is within a certain range within a certain look-ahead time. Consider the two aircraft AC_1 and AC_2, shown in Figure 13 (a), experiencing a head-on conflict with a distance at CPA (d_{CPA}) of 0 nmi. Assuming that only AC_1 makes full conflict resolution maneuver, the maximum path deviation for AC_1 is equal to the safe separation distance. Assuming that this resolution were to cause a subsequent conflict with a third aircraft (AC_3), the maximum d_{CPA} with this new aircraft must then be less than the safe separation distance.

From Figure 13 (a), it can be inferred that there is a potential for a non-conflicting aircraft AC_3 to come in conflict with an aircraft AC_1, after AC_1 has resolved an existing conflict with an aircraft AC_2, if the d_{CPA} between AC_1 and AC_3 is less than $2 \cdot d_{sep}$. Based on this, the influence aircraft are identified as any aircraft for which $d_{sep} \leq d_{CPA} < 2 \cdot d_{sep}$. The Influence Zone (IZ) is then depicted as shown in Figure 13 (b) as a region of the ring with a safe separation distance as $5nmi$. In the multi-aircraft situations, the conflict status takes the priority over the status of influence for a given aircraft. In other words, an aircraft can be called influence aircraft only if it is not in conflict with any other aircraft and falls in the IZ of another aircraft.



(a) Identifying influence aircraft



(b) Representation of the IZ

Fig. 13. The Influence Zone of an Aircraft

V. Experiment

To study the coordination behaviour of multiple pilots in a distributed environment and to test the framed hypotheses (mentioned later in the current section), a human-in-the-loop experiment was conducted and the compared against an automated conflict resolution algorithm as a baseline.

A. Method

1) Subjects and Background: Six groups took part in the human-in-the-loop experiment with a total of 41 participants. The participants were specifically chosen from field of aerospace engineering at the master level of studies as the lowest qualification. Practical constraints lead to conduct the experiments with as many participants as were present at the time of the experiment (5, 7 , 7, 7, 7 and 8 in each group). In cases of groups with less than eight participants, unassigned aircraft were left as uncontrolled aircraft, i.e., the strategy inherently was assumed to make no manoeuvres irrespective of the situation.

2) Independent Variables: From the proposed C-I Classification, the number of conflicting aircraft, m (from C_m), and the number of influencing aircraft, n (from I_n), were identified as the within-subjects independent variables.

3) Scenarios: Based on the independent variables, four scenarios were finalized and tested in the experiment. The finalized scenarios are shown in Figures 14-17. The levels of independent variables chosen to study the effect of influence aircraft on already existing conflicts by first analyzing them.

The values and the number of levels of each independent variable were chosen based on multiple criteria. The primary criterion being the evolution of the conflict geometries based on the interaction between different aircraft. The secondary criterion being the practical constraints such as the duration of the experiment, and the availability of physical resources. *Bluesky*, an open-source air traffic simulator was used to design and analyze traffic scenarios using the Modified Voltage Potential (MVP) algorithm.

First, the conflict-only scenarios were designed by analyzing the interaction with every additional aircraft starting from two aircraft. Then influence aircraft were placed and analyzed by observing the interaction with neighboring air traffic. Some influence aircraft were deliberately designed to come in conflict, while some were designed to remain as an influence and

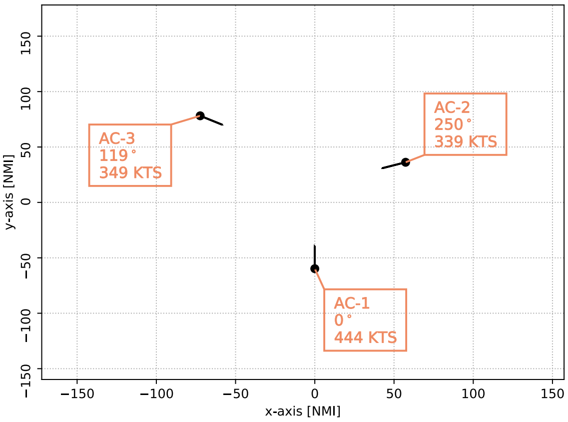


Fig. 14. Conflict only scenario C_3

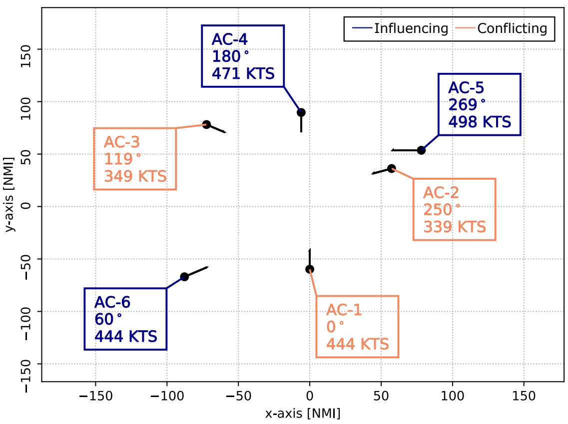


Fig. 15. Conflict-Influence scenario C_3I_3

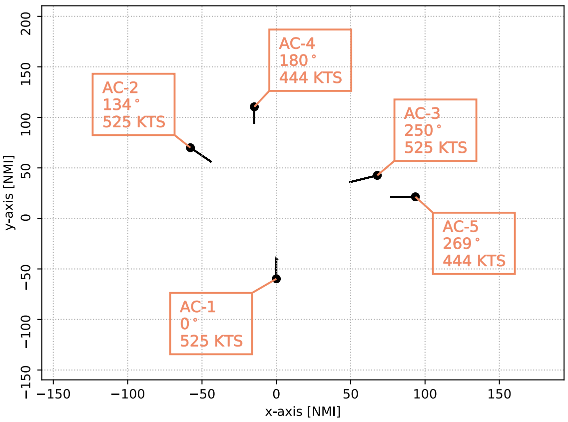


Fig. 16. Conflict only scenario C_5

never turn into conflicting aircraft.

The levels of the independent variables are shown in Table I. If the influence count is equal to zero, it means that it is a conflict only scenario (C_m).

4) Instructions: A briefing document was sent to the participants to prepare them with the setup of the modern glass cockpit and autopilot controls of the aircraft. During the experiment briefing, the participants were instructed to maintain the initial speed and heading while flying on an indicated reference path, unless a situation threatening the safe separation was encountered. The participants were instructed to decide on whether they had to make a maneuver or not. If they decided to make a maneuver, the sort of maneuver was also to be decided by them. For the resolution of conflicts, no coordination rule was specified. All the participants were instructed to gather all the information required to fly safely from the SSD presented to them. Further, the good-practices that were encouraged and the bad practices that were discouraged were also discussed.

5) Apparatus: The experiment was conducted in a computer lab with distributed simulation capabilities. A standard computer station with a mouse and key-board was set-up for each participant. All the computer stations had the same settings with negligible differences.

6) Aircraft Characteristics: The aircraft model used was a Boeing B703 model due to the wide range of operational velocities it had and due to its availability in the software. The look-ahead time ($t_{look-ahead}$) for all the aircraft was set to 300 s since previous research had shown that it was sufficient to strategize and resolve the conflicts in that time [6], [34]–[37].

7) Simulation Settings: The experiment was conducted using a multi-player aircraft simulation software called as the *ASASMultiActor*. The simulation speed was tested and adjusted to run at four times the standard speed by considering aspects of boredom in idle routes and overall duration of the experiment.

The display set up contained two aspects: simulation and questionnaires. For the simulation side, the participants saw three main windows: the Navigation Display (ND), the Mode Control Panel (MCP) and the Electronic Flight Instrument System control panel (EFIS control panel). The links for

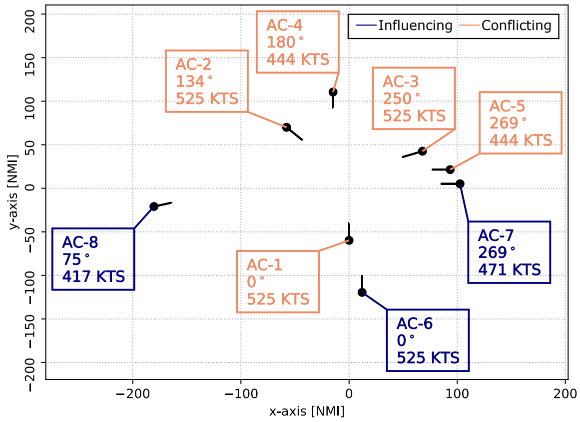


Fig. 17. Conflict-Influence scenario C_5I_3

TABLE I
INDEPENDENT VARIABLES

Independent Variable	Level 1	Level 2
Conflict Count (m)	3	5
Influence Count (n)	0	3

two questionnaires which opened in a web browser was in a separate window.

The ND was set up to show the only information required for the experiment such that it looked like one of the available mode options of the ND. As shown in Figure 18, there were three main features in the ND. First, located at the bottom of the ND was the Solution Space Diagram for CD&R. Second, to simulate a trajectory between two waypoints from a flight plan, a straight magenta line that acted as a reference path was used. The reference path began at the starting location of the aircraft and was directed towards the starting heading of the given aircraft. Third, indicated in Magenta color on the top left corner was the reference Indicated Air-Speed. This was the indicated airspeed at which respective aircraft flew when the simulation started. The default ND range was set to 20 nmi.

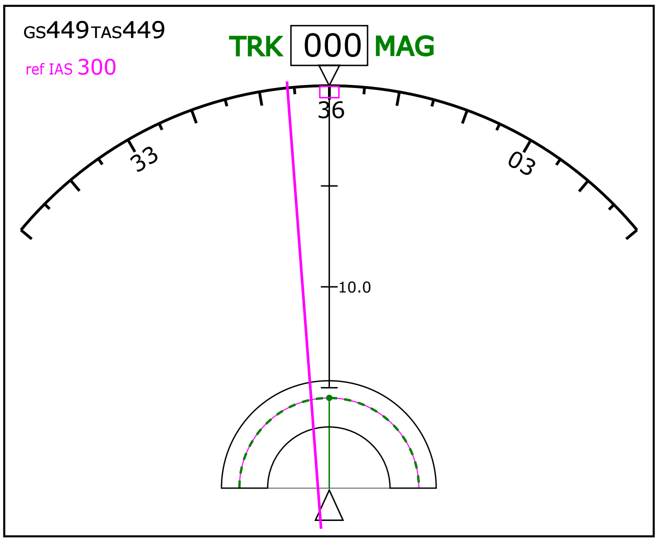


Fig. 18. The Navigation Display set up for the experiment: the reference indicated airspeed and the reference path to follow indicated in magenta

A module displaying a Boeing 737's MCP was used to record the input from the user. Indicated airspeed and heading knobs were the only permitted control knobs. A module displaying Boeing 737's EFIS Control Panel was used to provide the feature of changing the range of the ND. The knob was to be used only in case the reference track was beyond the display range of the ND.

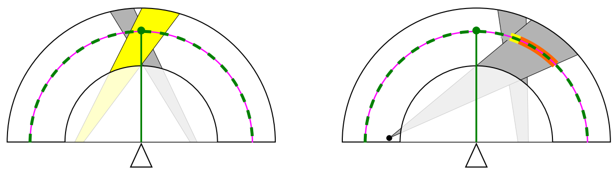
8) Alerting Levels in the SSD: The FBZ of the SSD was color-coded based on the time to LoS (t_{LoS}) to provide visual cues on the severity of the respective conflict. Based on the previous research [28], [38], [39] and analyzing the Solution Space Diagram in the experiment setup, the proximity of a conflict was color-coded based on the values of t_{LoS} as shown in Table II.

A gray alert was a neutral alert indicating there was an expected conflict within the $t_{look-ahead}$. Following this were the remaining alert levels with priority increasing to yellow, then amber and finally red color. The red alert indicated the highest level of priority requiring quick action to avoid an intrusion. A sample of color-coded SSD is shown in Figure

TABLE II
COLOR CODES OF THE SSD

Color	Conflict t_{LoS}bin
Gray	$300s < t_{LoS} \leq t_{look-ahead}$
Yellow	$180s < t_{LoS} \leq 300s$
Amber	$90s < t_{LoS} \leq 180s$
Red	$0s < t_{LoS} \leq 90s$

19 (a).



(a) Forbidden Beam Zone color-code (for conflicting FBZ only)

(b) Heading band color-code (for non-conflicting FBZ only)

Fig. 19. Color-coded SSD

9) Heading Bands for Influence Aircraft: For aircraft that were identified to be the influence aircraft, the intersection of the FBZ with a ring of the radius of current speed (indicating different heading with current speed) was color-coded (Figure 19 (b)). The color-code used was the same as that used for the conflicting FBZ. The heading bands were used to have an insight on the severity of conflicts one may encounter due to knock-on effects.

10) Dependent Measures: The dependent measures of the experiment are presented in Table III.

TABLE III
OBJECTIVE DEPENDENT VARIABLES

Dependent Measure	Assessed for	Description
n_{int}	Safety	Number of intrusions
I_{sev}	Safety	Intrusion severity
T_{inInt}	Safety	Duration of intrusion
IPR	Safety	Intrusion Prevention Rate
n_{cfl}	Safety	Number of conflicts
$d_{CPA_{cnf}}$	Efficiency	Distance at CPA for conflict
T_{inCnf}	Efficiency	Duration in conflict
T_{return}	Efficiency	Time to return to original path
Added track	Efficiency	Extra distance traversed
Path Deviation	Efficiency	Deviation from the initial path
Speed Changes	Efficiency	Decision changes for speed
Heading Changes	Efficiency	Decision changes for heading
SSD Complexity	Efficiency	Area of Conflict in SSD (%)

Five metrics were used to measure the safety performance of the airspace. The number of intrusions (n_{int}) was the most important factor. Since intrusion was not necessarily a collision, further assessment was made to study the severity of intrusions. For the horizontal situation, the intrusion severity (I_{sev}) was calculated by measuring the distance at CPA (d_{CPA}) as a fraction as shown in Equation 1 [40].

$$I_{sev} = \frac{RPZ - d_{CPA}}{RPZ} \tag{1}$$

The next measure quantifies the ability to resolve conflicts as the proportion of intrusions avoided without experiencing an intrusion. This metric termed as Intrusion Prevention Rate (IPR) and is calculated from the number of conflicts the number of intruders as shown in Equation 2 [40].

$$IPR = \frac{n_{cfl} - n_{int}}{n_{cfl}} \quad (2)$$

The number of conflicts (n_{cfl}) in a scenario was also used as a dependent measure to analyze the safety of the airspace.

Eight efficiency-related metrics were used to measure the performance of human actors. The d_{CPA} for the conflicting aircraft, the duration of time spent in a conflict, the time taken to return to the original path, the extra distance traveled due to maneuvers made, the deviation from the original track, the heading-change, and speed-change commands. And finally, the SSD complexity metric was used to gain insight into the evolution of complexity of the scenarios over time [41].

11) Questionnaires: Questionnaires were asked at the end of each run and at the end of the experiment. Table IV shows the respective measures from each questionnaire.

TABLE IV
QUESTIONNAIRE

At the end of each simulation	At the end of the experiment
Encountered Conflict	Most preferred conflict resolution strategy
Satisfaction for first conflict resolution	Reason for most preferred strategy
Alternate resolution approach than what was employed	Evolution of preferred strategies
	Familiarity of the setup prior to the experiment

The participants were first asked if they encountered any conflict. If they did, then questions regarding decisions made and strategies used were asked. The evolution of the scenarios is dependent on the individual decisions and strategies and the time at which they were implemented. In order to have an insight on strategies applied, the participants who encountered conflicts were asked if they were satisfied with the way the first conflict they encountered was resolved. Based on the answer to this, a follow-up question was asked to know if they wanted to change their strategy. If they answered positively, their alternative strategy was recorded.

In the end-of-the-experiment questionnaire, the participants were asked to indicate their most preferred strategy and the reason for the same to get an understanding of the overall conflict resolution strategies. They were also asked to comment on how their most preferred strategy came to be the most preferred by discussing on previously tried strategies. And finally, the familiarity of the participants with the setup of the experiment was asked to know if it had any influence on their performance.

12) Experimental Conditions and Experiment Matrix: All the participants were made to participate in every run by combining the experiment cases to avoid any idle participants. Scenarios C_3 and C_5 were combined by placing each case far from each other, such that there were no effects of interaction. In case C_5 two dummy aircraft were added far from the real scenario. Table V summarizes this modification and thus shows the three experimental conditions that were tested.

TABLE V
EXPERIMENT CONDITIONS

Experiment Condition	C-I Classification ($C_m I_n$)	Subjects Required		
		For scenario	Dummy	Total
Condition 1	C_3 & C_5	8	0	8
Condition 2	$C_3 I_3$	6	2	8
Condition 3	$C_5 I_3$	8	0	8

Based on the experimental conditions and six groups of participants, the experiment matrix was constructed as shown in Table VI for six groups of participants.

TABLE VI
EXPERIMENT MATRIX

Group Number	Run Number		
	1	2	3
Group 1	Condition 1	Condition 2	Condition 3
Group 2	Condition 2	Condition 3	Condition 1
Group 3	Condition 3	Condition 1	Condition 2
Group 4	Condition 1	Condition 2	Condition 3
Group 5	Condition 2	Condition 3	Condition 1
Group 6	Condition 3	Condition 1	Condition 2

13) Procedure: Each run in the training phase and the measurement phase had the same procedure as follows:

Step 1: Once the simulation is set and the count-down is announced, get ready for the start of the simulation

Step 2: once the simulation starts, maintain the current heading, speed and reverse on the initial reference path.

Step 3: Analyze the SSD and watch for conflicts.

Step 4: If a conflict is encountered, analyze the SSD, decide on what to do (change speed, change heading, change both or change neither).

Step 5: If an evasive maneuver is executed, return to initial reference path, speed and heading (order independent).

The simulation was stopped once all the participants returned to the original state and path. A questionnaire had to be completed.

This procedure repeated for all the experiment conditions. After the last run, the end-of-the-experiment questionnaire had to be answered.

B. Hypotheses

Based on the analyses using the MVP algorithm and analyzing experimental situations manually, several hypotheses were framed.

In every scenario, a way to avoid any intrusion was always possible to the naked eye. Hypothesis 1: *For the traffic scenarios chosen, the airspace is expected to be safe without any intrusion.*

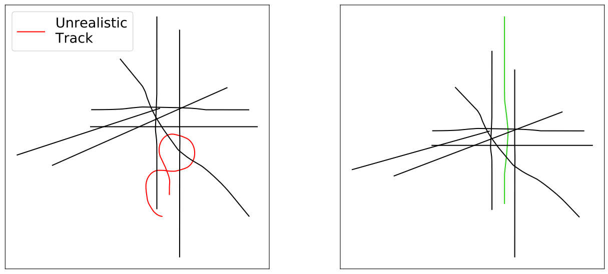
The CD&R algorithm in *Bluesky* forces equal coordination of all aircraft participating in the conflict. This behavior is difficult to find in humans without explicit instructions on coordination. For this human-in-the-loop experiment, there is no coordination rule enforced. This is hypothesized to give rise to aspects of unsynchronized maneuvers from individual actors, which in turn lead to a varying level of coordination of resolution.

Hypothesis 2: *For the traffic scenarios chosen, the humans performance is expected to be less uncoordinated than MVP.*

The uncoordinated behavior will affect the overall time taken to resolve to the conflicts and the resulting complexity of the air traffic.

Hypothesis 3: *For the traffic scenarios chosen, the MVP is expected to have higher efficiency in the resolution of conflicts than humans.*

Hypothesis 4: *For the traffic scenarios chosen, the MVP is expected to have lower air traffic complexity than humans.*



(a) Unrealistic trajectory (red)

(b) Result of trajectory data imputation

Fig. 20. A case of data imputation

VI. Results

The data from the familiarization and training runs are discarded. From the measurement runs, the data from experiment Condition 1 (Table V) was split into the respective scenarios. The data from experiment Condition 2 for the two dummy aircraft was discarded. Finally, the time scales of the human-in-the-loop and the MVP algorithm are matched by multiplying with respective simulation speed factors.

A. Deviant Results and Data Imputation

Four out of 132 aircraft trajectories (6 groups times 22 trajectories) showed highly unrealistic trajectories from the participants (one of such scenario is shown in Figure 20 (a)). This data would be destructive to use for further analyses and would serve no purpose in providing reliable conclusions. However, discarding all the data from the associated group is an expensive option. Hence, data imputation by replacing the unrealistic trajectory with the one flown by another group's participant in a realistic manner for the same aircraft was considered. The analyses of the performance measures are averaged over the group. Since only one trajectory is imputed, the remaining trajectories are still unique to the group, creating unique averages for each group. Hence, this method of data imputation was applicable. If there was a fit found without any additional modifications to borrowed trajectory, only then the data imputation was considered successful (Figure 20 (c)). All the four unrealistic trajectories were imputed successfully. Although the effect of data imputation is not fully measurable in a quantifiable manner, an effort was made to analyze the correlation between the instantaneous path deviation and instantaneous SSD complexity of the modified and borrowed scenarios. It was found that the imputation did not have any significant effect on the correlation of these parameters. Moreover, it is justified to perform further analyses on the imputed dataset which is realistic than the raw data which is certainly unrealistic. Further discussion on what lead the subjects to perform in this manner is discussed in Section VII.

B. Results

The results of the effects of the independent variables on the objective dependent measures are presented and discussed alongside the results of the MVP algorithm. In some cases, the average value of the dependent measure over the group is not sufficient to get a complete insight on the severity. In such cases, an analysis is done on the extreme values of the dependent measures (minimum and maximum values). Statistical tests were done to check if there was a statistical significance of these effects on the dependent measures. The Shapiro-Wilk's normality test was used to check the normality of the data [42]. For normally distributed measures, the parametric test repeated measures two-way ANOVA [43] was performed. For non-normally distributed measures, the non-parametric test Freidman's two-way ANOVA [43] using the χ^2 statistic was used.

1) Safety Related Measures: There was only one intrusion observed in all of the scenarios simulated in human-in-the-loop experiment. Upon inspection, this intrusion was found to be resulting from two uncontrolled aircraft from the group with five participants. The intrusion observed resulted in d_{CPA} of 4.1 nmi and lasted for a duration of 31.6 s. Since the intrusion that was observed in the human-in-the-loop experiment was not caused by the human, it is ignored. Therefore, no further analyses are done on dependent measures related to intrusions (I_{sev}, T_{inInt}, IPR). Further, the MVP algorithm also resulted in no intrusions whatsoever.

Figure 21 shows the effect of the independent variables on the overall number of aircraft that encountered a conflict. Interestingly, for scenario C_5 , the number of aircraft involved in a conflict for some groups is less than the designed number of aircraft in conflicts (5). That is, the participants were able to see the conflict as a gray colored FBZ and moved out of the FBZ even before it came close enough to a yellow alert level. This indicates that the conflicts were resolved ahead in time that the designed conflicts were not conflicts anymore. For the cases of influence aircraft, it is seen that on average, the influence aircraft experience a conflict at some point. Statistical tests were not performed because the number of conflicts in C_3 was constant. Further, the MVP algorithm is observed to involve all the aircraft in the given scenario. Comparing the performance of MVP algorithm with human performance, it can be seen that humans were equal or better in terms of the number of aircraft involved in conflicts.

2) Distance to CPA for conflicts: Figure 22 (a) shows the effect of the independent variables on the average d_{CPA} for the conflicting aircraft. Comparing between the scenarios C_3 - C_5 and C_3I_3 -C_5I_3 (from here on referred as *Comparison 1*) shows that the increase in the number of aircraft in conflict had no consistent trend. Comparing the scenarios between

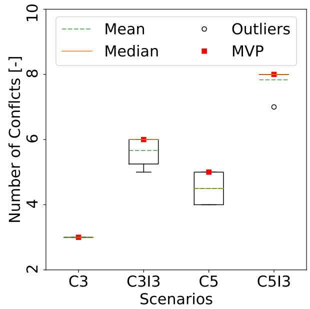
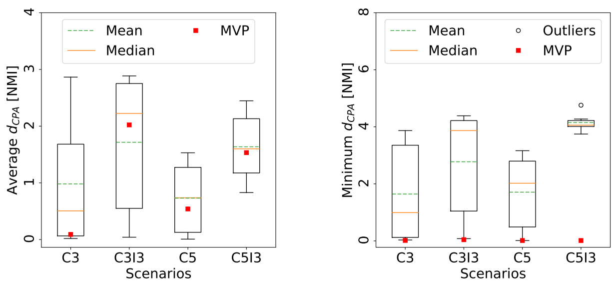


Fig. 21. Effect of the independent variables on the number of aircraft involved in conflicts

C_3 -C_3I_3 and between C_5 -C_5I_3 (from here on referred as *Comparison 2*) shows that the presence of the influence aircraft resulted in an increase in the average d_{CPA} . Statistical tests revealed no significant effects. The average human performance is close to that of MVP's except for scenario C_3 , where MVP had nearly 0 nmi for average d_{CPA}.

Figure 22 (b) shows the effect on the minimum d_{CPA} for the conflicting aircraft. *Comparison 1* shows that the increase in the number of aircraft in conflict had no consistent trend. *Comparison 2* shows that the presence of the influence aircraft resulted in an increase in the minimum d_{CPA} distance. Statistical tests revealed had no significant effects on the minimum d_{CPA} . The MVP algorithm maintained the lowest possible d_{CPA} for conflicts for all the scenarios.



(a) Average d_{CPA}

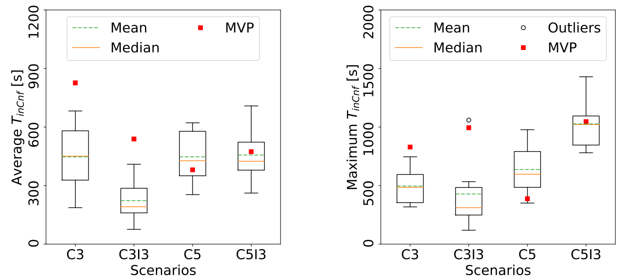
(b) Minimum d_{CPA}

Fig. 22. Effect of the independent variables on the d_{CPA} for conflicts

The possible reasoning for higher d_{CPA} for conflicts in humans is because humans react much earlier that the MVP. This directly results in having a higher d_{CPA} when the aircraft are within the $t_{look-ahead}$range. The main observation here is that humans appear to be resolving conflicts early.

3) Time in Conflict: Figure 23 (a) shows the effect on the average T_{inCnf}. *Comparisons 1 and 2* both show an inconsistent trend. Statistical tests revealed no significant effect on the average T_{inCnf}. The MVP, on the other hand, shows a decreasing average T_{inCnf} for *Comparison 1*.

Figure 23 (b) shows the effect on the maximum T_{inCnf}. *Comparison 1* shows an inconsistent trend, while *Comparison 2* shows that the presence of the influence aircraft resulted in an increased maximum T_{inCnf}. A direct relation is obvious and expected for this measure. Statistical tests revealed that the effect of the number of the conflicting aircraft (m) was significant $(F(1,5) = 7.160, p = 0.044)$ and, the interactions resulted in a significant effect $(F(1,5) = 10.937, p = 0.021)$. Compared to MVP algorithm, humans seem to clear the conflicts early.



(a) Average T_{inCnf}

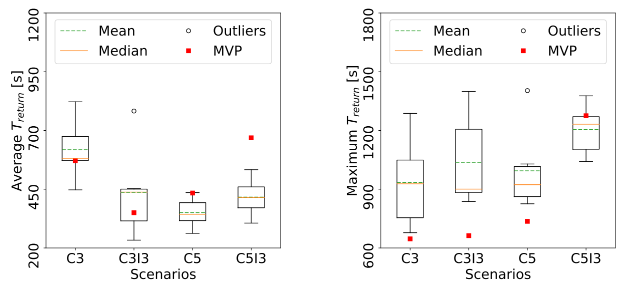
(b) Maximum T_{inCnf}

Fig. 23. Effect of the independent variables on the T_{inCnf}

This result further supports the previous inference that humans resolved the conflicts quickly because humans reacted early to the conflicts and had the chance to resolve them quickly.

4) Time to Return to the Original Track: Figure 24 (a) shows the effect the average time taken to return to the original track after making a resolution maneuver. *Comparisons 1 and 2* show an inconsistent trend. Statistical tests revealed the effect of m was significant $(F(1,5) = 54.366, p = 0.001)$ and, the effect of the interactions was significant $(F(1,5) = 8.804, p = 0.031$. The MVP algorithm also showed a similar inconsistency, however, for higher number of aircraft, the MVP algorithm took more time to return to the original track than the humans did.

Figure 24 (b) shows the effect on the maximum T_{return}. *Comparisons 1 and 2* show that an increase in the maximum T_{return}. Statistical tests revealed that there was no significant.



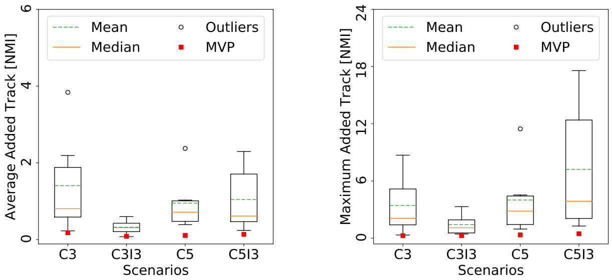
(a) Average T_{return}

(b) Maximum T_{return}

Fig. 24. Effect of the independent variables on the time to return to the original track

The humans are seen to show an inconsistent behavior. This was expected since there is no coordination on when everyone starts to resolve a conflict. This leads in different types of resolutions and eventually different times to return to original track. An important aspect to note here is that the humans, on average, returned to the original track faster than MVP when there were more number of aircraft in the scenario.

5) Added Track Miles: Figure 25 (a) shows the average added track miles. Statistical tests showed a significant effect with pairwise comparison between C_3 - C_3I_3 ($\chi^2(3) = 9.80$, adjusted significance $p = 0.022$). For the maximum added track miles (Figure 25 (b)), there was no significant effect.



(a) Average Added Track (b) Maximum Added Track

Fig. 25. Effect of the independent variables on the added track miles

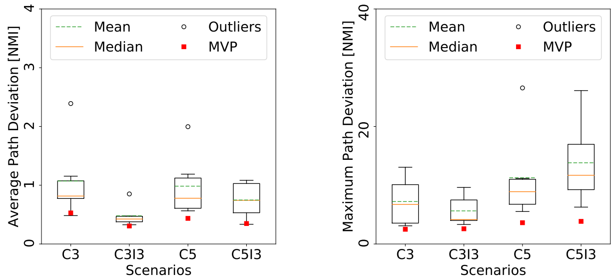
An important observation here is that humans in almost all the cases had higher added track miles than the MVP. MVP is a robust algorithm, and has the ability to make very small and accurate maneuvers, whereas humans make approximated maneuvers. However, this performance from the humans may also be attributed lack of training from humans to have more accuracy in their resolutions.

6) Path Deviation: Figure 26 (a) shows the effect on the average path deviation. In scenarios with no influence aircraft, the number of conflicting aircraft seemed to have no effect on the average path deviation. For scenarios with influence aircraft, there was a decrease in the average path deviation with the increase in the number of conflicts. Statistical tests showed that the data was non-normal and the effect was significant ($\chi^s(3) = 9.600, p = 0.022$) for pairwise comparisons of scenarios C_3I_3 -C_3 and C_5I_3 -C_3.

Figure 26 (b) shows the effect of the independent variables on the maximum path deviation. In scenarios without influence aircraft, an increase in the number of conflicts is seen to cause an increase in the maximum path deviation. And in scenarios with influence aircraft, a similar trend is observed. The comparison of scenarios C_3 -C_3I_3 and C_5 -cfour shows no particular trend. Statistical tests revealed that the data was non-normal and the effect was significant (($\chi^s(3) = 9.000, p = 0.029$)) for pairwise comparison of the scenarios C_3I_3 -C_5I_3.

Compared to the performance of the MVP, the trend in humans seems to be the same as that observed in the MVP. However, the humans had a higher maximum path deviation than the MVP algorithm. This observation is not surprising since the MVP algorithm, unlike humans, can accurately traverse the intended resolution maneuvers without requiring a factor of safety. Also, the MVP algorithm, for the tested scenarios, always resulted in implicit coordination.

7) Speed Change Commands: Figure 27 (a) shows the effects on the average speed-change commands. *Comparison 1* show that an increase in the number of conflicting aircraft results in reduced speed-change commands. *Comparison 2* shows that the presence of influence aircraft had no effects.

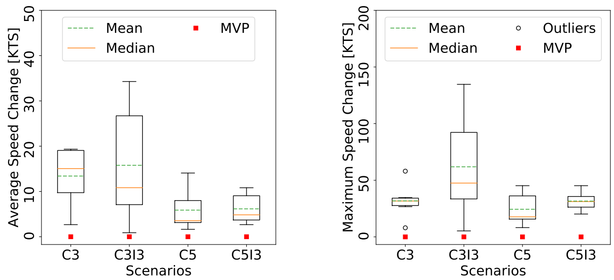


(a) Average Path Deviation (b) Maximum Path Deviation

Fig. 26. Effect of the independent variables on the path deviation

Statistical tests revealed that the effect of the number of conflicts was significant ($F(1,5) = 18.07, p = 0.008$).

Figure 26 (b) shows the effect of the independent variables on the maximum speed-change commands. *Comparison 1* shows a decrease in the maximum speed-change commands. *Comparison 2*, shows an increase in the maximum speed-change commands. Statistical tests revealed that the presence of the influence aircraft had significant effect ($F(1,5) = 11.932, p = 0.018$).



(a) Average Speed-Change Commands (b) Maximum Speed-Change Commands

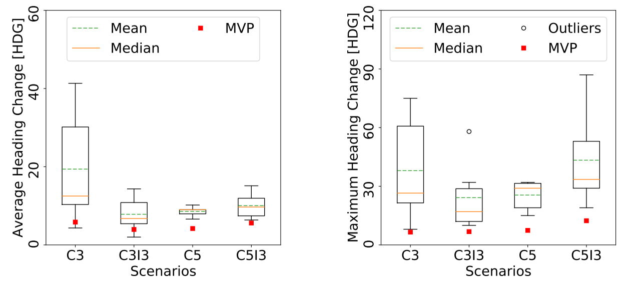
Fig. 27. Effect of the independent variables on the speed change commands

For the scenarios tested, the MVP algorithm made no speed-change commands whatsoever. The MVP algorithm is more efficient in flying than humans regarding the speed-change commands executed. On the other hand, the fact that humans were not given any coordination rule to follow, gave them the flexibility to use the speed-change commands without having to worry about performance.

8) Heading Change Commands: Figure 28 (a) shows the effect on the heading-change commands. *Comparisons 1 and 2* show no consistent trend. Statistical tests revealed that the presence of influence aircraft had significant effects ($F(1,5) = 10.17, p = 0.024$). Comparing the performance of the human with that of the MVP algorithm, a similarity in the trend is observed. Although the trend is the same, the MVP algorithm, on average, made smaller changes in the heading than the humans.

Figure 28 (b) shows the effect on the maximum heading-change commands. The results show nearly the same trend as for the average heading-change but with higher magnitudes.

The statistical tests revealed that none of the independent variables had any significant effects. The MVP algorithm resolves conflicts with lower maximum heading-change commands than humans.



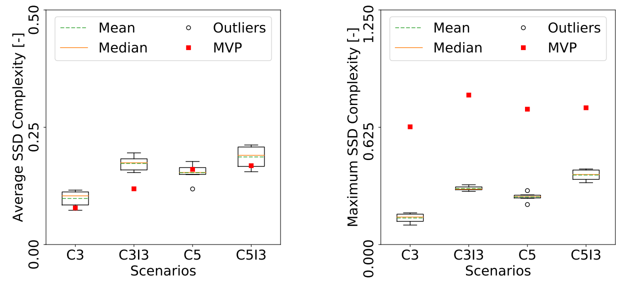
(a) Average Heading Change Command (b) Maximum Heading Change Command

Fig. 28. Effect of the independent variables on the heading change commands

9) SSD Complexity: Figure 29 (a) shows the effect of the independent variables on the average SSD complexity averaged within each group (the average SSD complexity for each aircraft in time is calculated, and then the average of the averages for each aircraft is calculated). *Comparisons 1 and 2* show an increase in the SSD complexity. Another obvious aspect is that the SSD complexity is seen to increase with the number of aircraft in the entire scenario. This is obvious because more aircraft in a situation occupies more area in the SSD display. Statistical tests revealed that the effect of the number of conflicting aircraft was significant ($F(1,5) = 152.954, p < 0.001$), the effect of the presence of influence aircraft was significant ($F(1,5) = 194.835, p < 0.001$), and the interaction effects were also significant ($F(1,5) = 25.326, p = 0.004$). The MVP algorithm also showed a similar trend, however, had lower SSD complexities than the average human performance for the scenarios C_3 , C_3I_3 , and C_5I_3 .

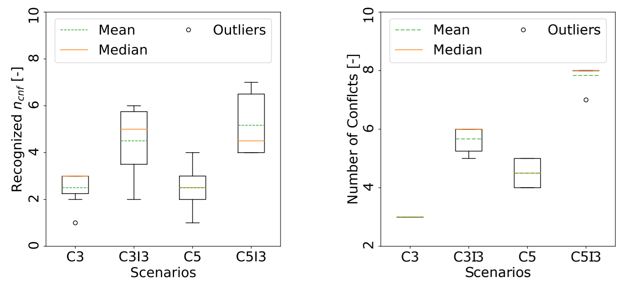
Figure 29 (b) shows the effect on the maximum SSD complexity averaged with each group (maximum SSD complexity for each aircraft in time is calculated, and then the average of the maximums for each aircraft is calculated). The maximum SSD complexity shows a similar trend to that of the average SSD complexity, however, with higher magnitudes. It is also seen that there is a very little variance in the complexities from each group across all the scenarios tested. Statistical tests revealed that the effect of the number of conflicting aircraft was significant ($F(1,5) = 18.019, p = 0.008$), the effect of the presence of the influence aircraft was significant ($F(1,5) = 52.277, p = 0.001$), and the interaction effects were significant as well ($F(1,5) = 29.852, p = 0.003$). Comparing the maximum complexities resulting from the MVP algorithm, once can observe that the maximum SSD complexities by humans, though had a similar trend, was considerably lower that that of the MVP algorithm's.

10) Subjective Measures: Deviant results observed before calls a check of integrity of the subjective measures. Therefore, before analyzing the subjective measures, a check is made on the number of participants that reported to have encountered a conflict. An exact match between the subjective measure and the objective measure indicates that the participants were able to recognize every conflict that was encountered. However, upon comparing Figures 30 and 21, the difference in the participant reported data and the objectively calculated number of aircraft in conflicts is evident. Therefore, for the subjective measures, no statistical tests are performed. However, a comparison is made on the available data.



(a) Average SSD Complexity (b) Maximum SSD Complexity

Fig. 29. Effect of the independent variables on the SSD complexity



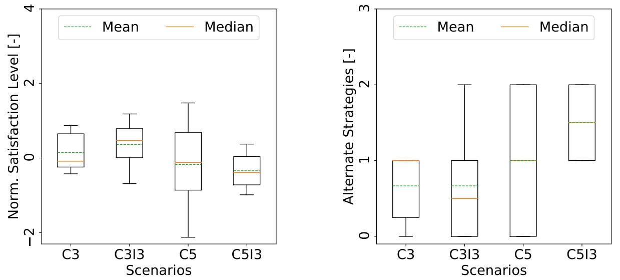
(a) Reported by subjects (b) Objectively calculated from aircraft states

Fig. 30. Number of aircraft in conflicts

The analysis on reflection of employed resolution method was done for those participants who reported to have encountered conflicts. Figure 31 (a) shows the normalized (per group) level of satisfaction for the resolution of the first conflict that was encountered. The higher the value of the normalized satisfaction was, the more satisfied the participants were with their decision. *Comparison 1* shows a lower level of satisfaction for the resolution of the first conflict for scenarios with increasing conflicts. *Comparison 2* shows that the presence of influence aircraft has no consistent trend.

A total of 23 participants indicated that they would change their strategy for the resolution of the first conflict they encountered. Most of them indicated that their new strategy would have been to respond to the conflict at a later point of time than when they resolved it. By doing so, they informed that it would have reduced the deviation from their path, reduced the number of decision changes or reduced the time taken to resolve the conflict.

Table VII shows the most preferred resolution method for the conflict resolution. Most of the participants who indicated "global conflict resolution" as their most preferred strategy,



(a) Normalized Level of Satisfaction for Resolution of the first Conflict

(b) Number of subjects proposing alternate strategies for the first conflict

Fig. 31. Subjective Measures: the level of satisfaction and alternate strategies

thought so because it required less effort to clear all the conflicts at once. Most of the participants who indicated "sequential conflict resolution" as their most preferred strategy thought so because they felt that the FBZ of the conflicts evolved too frequently to have one manoeuvre to resolve all the conflicts. Further, they indicated that resolving conflicts sequentially, they were able to stay closer to the original reference path. And most participants who indicated "a combination of both global and sequential conflict resolution" as their most preferred strategy, thought so because it gave them more flexibility in manoeuvre making decisions based on individual situations. There were also a few participants who opted to do nothing. This preference started with their intent to wait and decide on the maneuver to execute by first observing the FBZ. However, the intruders resolved the full conflict for them each time. And hence their preferred method was to stay on the original track until the situation demanded to move out of it.

TABLE VII
MOST PREFERRED RESOLUTION METHOD

Resolution Method	Counts
Global conflict resolution	15
Sequential conflict resolution	6
A combination of global and sequential conflict resolution	16
None	4

Some participants also noted on the information provided by the color-coded heading bands. They informed that the heading-bands enabled them to prioritize and deliberately make conflicting maneuvers to resolve conflicts globally. Considering that participants were biased with prioritizing neither speed nor heading resolutions, they made maneuvers using both the methods almost equally.

C. Observations During the Experiment

During the experiment, an observation was made on one of the participants who displayed one of the unrealistic behaviors (seen in Figure 20 (a)). Further questioning of the participant during the debrief clarified that the participant understood the concept of resolution of conflicts using the SSD. However, there was no clarification found as to why exactly the participant flew the aircraft in a that manner.

VII. DISCUSSION

The main observation from the safety parameters was that the airspace is observed to be safe for the tested scenarios when the aircraft are controlled by humans.

The results on the number of conflicts encountered and the performance measures reveal that humans reacted earlier than the MVP algorithm. In most cases, humans reacting earlier led to an inefficient resolution maneuvers. This feels like a safer maneuver within the untrained mind, however, this is not necessarily efficient since there is a higher uncertainty on the situation far advance in time. This is seen by the performances measured by d_{CPA} , time spent in conflict and, the time to return to original track. This was also recognized by a lot of participants in the questionnaires. However, since neither the training, nor the coordination rule gave them any sort of priority of the resolution maneuver the participants realized this over time and indicated the correction in retrospect. For a future experiment, it is recommended to have some sort of minimum analyzing time where the participants make no maneuver. Another suggestion would be to consider color-coding the FBZ in relation the number of aircraft in the vicinity. By doing so, there can be an option for early maneuvers in high density environments and relatively late maneuvers for low density environments.

The parameters added track miles, path deviation, speed change and heading change commands gave an insight inefficiencies resulting from lack of training in the approach towards a resolution. Clearly, the MVP algorithm had higher efficiencies in these parameters. Considering that the participant group was not a group of professional pilots meant that they had little to no background information on what are the inefficiencies involved in flight. Additionally, specifying no coordination rule gave more freedom for the participants to easily choose any resolution method. The inefficiencies are possible to be reduced by increased training. Given the background of the participants, the overall duration of the experiment may have been too squeezed to understand the efficient ways of using the SSD. It is known that the SSD can be used to resolve conflicts very efficiently [23]. A recommendation to this end would be to invite candidates with sufficient background in the concepts of the SSD or to have increased training.

The average performance of the humans was more inconsistent than the MVP across various efficiency parameters. One of the major factors for inconsistency in the performance is the lack of experience within the participants. Most of the participants, were from aerospace engineering background, but were not experienced in the concepts of the presented experiment. The learning curve of the participants in the understanding of the SSD and using it in the situations presented is also a contributing factor. Unlike a single human participant, it is not possible to track the training curve for the entire group. It was also evident with some performances that the participants were not all able to cope well with the concepts explained during the experiment briefing. This is mentioned to appreciate that the time constraints of the experiments places very high requirements on the prerequisite knowledge of the participants of the experiment. This inconsistency in the level of understanding started at the briefing level and propagated to subsequent steps of the experiment. The number of traffic scenarios that were tested were also limited due to time constraints on the duration.

Further, the resolutions were predicted and observed to be uncoordinated due to different reaction times and strategies. This is also seen in the SSD complexity graphs which shows a lot of incoherence. This may be attributed to different learning curves of individual participants. There was no way of maintaining the same level of training for all participants.

An important learning and a recommendation would be to have a thorough screening of the participants with a prior test of knowledge on the usage of the experiment setup. Rather than a standardized training, a personalized training (training till a certain performance level is met) would bring all the participants to the same performance level. This will not only ensure reliable participant group, but also the training level of the participants will be consistent.

The scenarios tested were not randomized, but rather designed. Though the scenarios were designed with extreme care, they are not representative of the numerous possibilities of reality. Considering that humans have shown to act in safe manner in this experiment, it is recommended to explore different scenarios. With the right training, a similar behaviour is expected no matter the scenario.

Based on the results, several hypotheses were tested. *Hypothesis 1* was made since it was confirmed that the airspace was safe for the scenarios tested when human actors are controlling the aircraft. *Hypothesis 2* was made since humans made a lot of uncoordinated maneuvers which led to deliberate conflicts. *Hypothesis 3* could not be confirmed since the average time in conflict was sometimes more for humans and sometimes less when compared to the MVP algorithm. *Hypothesis 4* could not be confirmed since the average SSD complexity was observed to be nearly the same for humans and the MVP algorithm.

VIII. Conclusions

In this research, an insight in the area of coordination in multi-actor self-separation was provided by conducting a human-in-the-loop experiment using the SSD. Specific scenarios were designed and simulated in the experiment to study the safety performance of the airspace and performance behavior of multiple pilots using the SSD. Results of the experiment showed that the SSD sufficiently supported humans in the maintenance of the minimum safe separation between aircraft for the scenarios tested. In terms of safety, humans were able to coordinate self-separation manoeuvres using the SSD such that the performance nearly equaled to that of the MVP algorithm. An important outcome observed was that the humans were sometimes better at avoiding conflicts altogether by monitoring the situation further in time as compared the MVP algorithm. In terms of performance, the humans were observed to make safer manoeuvres by sacrificing the efficiency of flight, while the MVP algorithm solves in an efficient manner, but with higher risk of breach of the safe separation.

Therefore, it can be concluded that humans using the SSD for CD&R for the scenarios tested can in fact operate safely in an airspace without any particular coordination rule, but with an instruction to maintain the minimum separation. The scenarios tested within this experiment, though limited, have provided an important insight on the coordination of multiple actors in self-separation in a distributed system using the SSD for CD&R .

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Part II

Master of Science Thesis Book of Appendices

Appendix A

Literature Studies (already graded)

THIS APPENDIX IS ALREADY GRADED AS PART OF PRELIMINARY THESIS

A-1 Terms and Definitions

Before going any further, some important terms which will be used in later context are defined[1]. The terms that have their value fixed will be discussed based on the available literature.

1. **Separation minima**: In order to facilitate safe navigation of aircraft in controlled and uncontrolled airspace, national authorities and International Civil Aviation Organization (ICAO) has laid out vertical and horizontal separation standards. When surveillance systems are used (based on radar, Automatic Dependent Surveillance - Broadcast (ADS-B) or Multilateration (MLAT)) the minimum horizontal (aka lateral) separation is 5 Nautical mile (nmi) and the minimum vertical separation is 1000 ft as prescribed by ICAO Doc 4444. Since this is based on radar and/or ADS-B and/or MLAT systems, the appropriate Air Traffic Services (ATS) authority may adjust it accordingly (described in detail in ICAO Doc 4444, 8.7.3.2 b)).
2. **Protected Zone (PZ)**: The PZ is defined as a cylinder of radius of 5 nmi and height of 1000 ft with aircraft at it's center. This PZ is defined based on the separation minima specified in the previous definition. For this research, only horizontal situation is being analyzed. Therefore, PZ from now on refers to only lateral separation zone, which is a circle.
3. **Closest Point of Approach (CPA)** (Figure A-1): For a given pair of aircraft, CPA is defined as the moment when the distance between the pair is the smallest. For 2 aircraft of parallel tracks, the CPA remains constant.

[1] New terms coined as a result of this research will be defined as and when they are introduced.

4. d_{CPA} (Figure A-1): For a given pair of aircraft, d_{CPA} is defined as the distance between the pair at the moment of CPA.

5. t_{CPA} (Figure A-1): For a given pair of aircraft, t_{CPA} is defined as the time required from the present moment until the distance between the pair is equal to d_{CPA}.

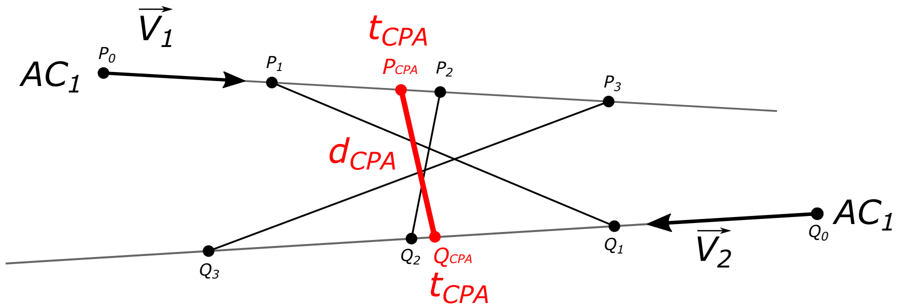


Figure A-1: Illustration of CPA, d_{CPA} and t_{CPA}
AC_1 and AC_2 are two aircraft with velocities $\vec{V_1}$ and $\vec{V_2}$ respectively. P_t and Q_t are positions of respective aircraft at different points in time ($t = 0$ is the initial step). P_{CPA}, Q_{CPA} and d_{CPA} are positions of and distance between AC_1 and AC_2 respectively at a time t_{CPA} after initial moment.

6. **Loss of Separation (LOS)**: The moment when the distance between 2 aircraft is so close that there is a breach of aircraft's PZ (distance between the corresponding aircraft is less than 5 nmi) is defined as a LOS[2]. Alternatively, it can be defined as the moment when $d_{CPA} < 5$ nmi.

7. **Time to Loss of Separation** (t_{LOS}) (Figure A-2): The time required from present moment until the moment of LOS is defined as t_{LOS}[3]. t_{LOS} is an important parameter that provides information on the conflict itself: the lower the t_{LOS}, the closer is the conflict.

8. **Look Ahead Time** (t_{LA}): Calculation of t_{LOS} for every detected aircraft would create too much warnings. Therefore, a time specifier, t_{LA} is defined to set an observation time which enables to ignore detecting a LOS from too far ahead in the future. Several research have adopted and tested different t_{LA} varying from 30, 60 and 120 s by Kelly (1999), to 300 s by J. M. Hoekstra, van Gent, and Ruigrok (2002) to 30 min by Chiang, Klosowski, Lee, and Mitchell (1997) to 6.5 h by Jardin (2005). As noted by Jardin (2005), as airspace density increases, the cascading effect of resolving conflicts too early by having a large look-ahead time incurs a large global penalty in efficiency. In a

[2]Please note: when visualizing scenario as a whole, the circle depicting PZ shown in the respective figures later in this report may have a radius of 2.5 nmi. This is done to visualize a LOS as an intersection of 2 PZ's (i.e., when 2 PZ's of radius 2.5 nmi touch, the distance between the corresponding aircraft is 5 nmi, which is a LOS). If this is indeed the case, it will be specified for the relevant figure.

[3]Note that t_{LOS} is different by definition from t_{CPA}. However, there may be cases where the value may be the same depending on the conflict properties.

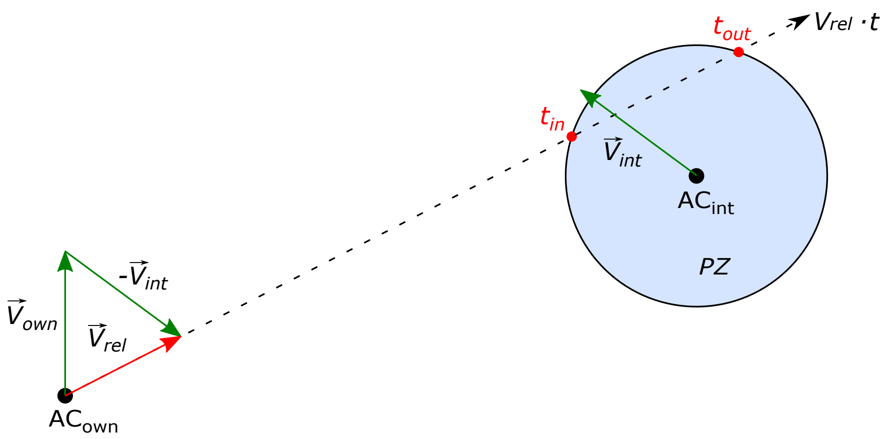


Figure A-2: Illustration of t_{LOS}
AC_{own} and AC_{int} are own aircraft and intruder with velocities $\vec{V}_{own}$ and $\vec{V}_{int}$ respectively. Calculating relative velocity vector, $\vec{V}_{rel} = \vec{V}_{own} - \vec{V}_{int}$ and integrating with time ($\vec{V}_{rel} \cdot t$) will give position of the own aircraft in time relative to the intruder. This is a case of conflict since the relative position vector passes through PZ of intruder. The time the PZ is breached (t_{in}) is the t_{LOS}.

research on Free Flight Air Traffic Management (FF) concept by J. M. Hoekstra et al. (2002), from initial trials for a look-ahead time, several conclusions were drawn:

- a long t_{LA} did not add much effectiveness and could potentially lead to unnecessary manoeuvres.
- lower limit for t_{LA} while maintaining an acceptable level of passenger comfort with a horizontal manoeuvre was in approximately 3 min for worst case scenario (head-on conflict with contemporary cruise speeds).
- Based on above conclusions, the authors chose a t_{LA} of 5 min for their research.

9. **Conflict** (Figure A-2): A conflict is the prediction of loss of separation within a certain t_{LA} when the present heading and speed are linearly interpolated.
10. **Intruder**: For a given conflict pair, each aircraft is an intruder from the perspective of the other since each of them is expected to breach one's own PZ.
11. **Conflict Angle**: The angle at which an intruder is oriented with respect to own aircraft heading.
12. **Conflict Detection:** The act or task or process of detecting a conflict by means of manipulating own state or observing intruder state is defined as conflict detection.
13. **Conflict Prevention:** The act or task or process of preventing the occurrence of a conflict by means of manipulating own state is defined as conflict prevention.
14. **Conflict Resolution**: The act or task or process of resolving a conflict after it has been detected is defined as conflict resolution.

A-2 Overview of Future ATM Research

During 1980's and 1990's, many researchers identified the need to invest and research in the field of aviation. Research conducted by English and Kernan (1976) on the prediction of air travel and aircraft technology to the year 2000 using the Delphi method indicated that air traffic will grow at slower rates than it had in the past (before 1976) and no major new developments in aircraft were foreseen. La Porte (1988) discusses the saturation of capacity of technologies used by then United States Air Traffic System (USATS). The report also identifies the areas that need to be attention with an initial peak at the topic. Perry and Adam (1991) identifies in a series of special reports on the steady growth of air travel, while the implementation of massive short- and long-term technological upgrade efforts in the US were being strained. Erzberger and Nedell (1989) writes that Jim Burnett, a former Chairman of the U.S. National Transport Safety Board said "In the short run, efficiency and safety will inevitably be in conflict". Erzberger and Nedell (1989) also discusses on restructuring of the FAA and that of Air Traffic Control (ATC) systems was essential to the continued growth of the air transport system. It was put forward that ATC reorganization would streamline the administrative, management and procurement procedures and enable the system to operate like a business.

This need for research for accommodating future aviation requirements spurred a lot of research in to this field from the 1990's. Stakeholders such as governments, companies and research institutes are working together to come up with the solution for this challenge. At the dawn of the 21st century, a plan was put forward. Next Generation Air Transportation System (NextGen) and Single European Sky ATM Research Joint Undertaking (SESAR-JU) are 2 of the biggest research programmes established by the US and Europe respectively at the beginning of this century. Following these programmes, other nations also followed in researching and upgrading their Air Traffic Management (ATM) system. A small overview of each of these programmes are given below.

A-2-1 NextGen

NextGen, is a comprehensive transformation of the National Airspace System (NAS). NAS is the collection of all the components (airspace, facilities, equipment, services, workforce, procedures, etc.) that enable the nation's air transportation system in the United States. NextGen will be safer, more reliable and more efficient, and will reduce the impact of aviation on the environment. National Aeronautics and Space Administration (NASA) in collaboration with the Federal Aviation Administration (FAA) and other industry partners develop the advanced automation concepts and tools. These tools provide air traffic controllers, pilots, and other airspace users with more accurate real-time information about the nation's traffic flow, weather, and routing. The greater precision of this information is a key enabler of NextGen. NASA's Aviation Systems Division is actively researching, developing and testing innovative automation solutions, including concepts, technologies, and procedures, to identify the most promising capabilities to achieve NextGen NASA (2016).

A-2-2 SESAR-JU

Though Single European Sky ATM Research (SESAR) programme was started in 2004, the private-public partnership came in 2007 when EUROCONTROL and European Commission together co-founded the SESAR-JU to research the future of ATM in Europe. In the SESAR-JU there are 19 members, who together with their partners and affiliate associations represent over 100 companies working in Europe and beyond. The main objective of this program was to define, develop and deploy what is needed to increase the ATM performance and build Europe's intelligent air transport system.

SESAR has set some performance ambitions to be met in it's European ATM Master Plan European-Union and Eurocontrol (2015). SESAR-JU is guided by this Master Plan to define, develop, validate and deliver the technical and operational solutions to modernize European ATM system. The key areas that are worked upon are:

- Airport operations
- Network operations
- Air traffic services
- Technology enablers

The aim of SESAR is to transform European ATM into a more modular, automated, interoperable, flight and flow-centric systems that take advantage of advances in digital and virtual technologies. The new ATM system takes all categories of vehicles from drones, general aviation and business aviation to commercial and military aircraft into account.

A-2-3 OneSKY Australia

OneSKY Australia is a partnership between Airservices Australia and The Department of Defense to develop a new integrated civil and military ATM system known as Civil Military ATM System (CMATS). The goal of OneSKY Australia is to make provide global interoperability in ATS and to unify civil and military ATM. The plan indicates final operational capability by the end of 2021 and final acceptance by 2023 (Australia & ICAO-APAC, 2015).

A-2-4 China-NASA collaboration

In an article by J.D.Harrington (2016) in September 2016, NASA and China announced their collaboration in ATM research that will advance the air transportation automation for U.S. and Chinese aviation operations in China. The work includes analyses of airport data from Chinese airports to identify and improve the efficiency in ATM systems.

A-3 Categories in ATM

A-3-1 Centralized ATM Systems

The centralized ATM system is the system where a ground station has the sole responsibility of maintaining safe separation between aircraft within it's specified airspace. The present day system of ATC is a centralized control. Majumdar and Polak (2001) suggested that the biggest limiting factor to increasing the capacity of current airspace is the Air Traffic Controller workload. Therefore, much research in centralized ATM is about a fully automated system or a system that will make the ATCO take a supervisory role.

Although there are researches focusing on centralized ATM systems with completely automation or with support system for an ATC Officer / Air Traffic Controller (ATCO) (supervisory systems), a bigger proportion of the research community believes that the latest technologies will enable us to move the responsibility of maintaining minimum separation from the ground to the cockpit.

A-3-2 Distributed / Decentralized ATM Systems / Free Flight (FF) Concept

The aviation industry has seen a tremendous growth in the previous century in terms of usage and technology. The introduction of automation to the industry has resulted in a change from mechanical push-pull rods and analog gauges to electronically operated fly-by-wire systems with glass cockpits and extensive flight management systems Billings (1991); Ellerbroek (2013); Lovesey (1977). Automation inside a cockpit has had a significant effect on the tasks performed by the cockpit crew Damos, John, and Lyall (2005).

The advent of new technologies such as on-board computing, GPS, etc., has made the possibility of a distributed ATM system a reality. In a distributed Air Traffic Management (distributed ATM), the responsibility of maintaining safe separation between aircraft is moved to the cockpit. This is made possible with Similar to centralized ATM research, research is being done on fully automated systems, as well as support systems for pilots.

Kosecka, Tomlin, Pappas, and Sastry (1997)'s research focuses on obtaining a set of manoeuvres to cover all possible conflict scenarios involving multiple agents using a certain planner in a decentralized ATM environment. The research discusses conflicts involving 2 and more than 2 agents under the assumption that the conflict resolution is homogeneous, are having same velocities and are willing to participate equally in the manoeuvre. Although this assumption is not realistic, the findings were interesting. The researcher concluded that the generalized overtake and generalized heading manoeuvres may be used to solve all possible conflicts between 2 aircraft. This enforces the classification of a 2 aircraft situation by making use of conflict angle[4]. For more than 2 aircraft conflict, a roundabout manoeuvre was suggested. This is too specific for the assumptions made in the research and may not reflect the reality in most cases. However, an important conclusion made by the researchers was that a proper classification of conflict scenarios and manoeuvres was a challenge.

[4]We will later study that this type of classification of conflicts between 2 aircraft using conflict angles is also a system that is proposed by ICAO to classify 2 aircraft conflict scenario.

Another aspect of research on decentralized ATM systems is the Tunnel in the Sky or 4-D space trajectories for aircraft. As noted by Mulder, Mulder, and Stassen (1999), the tunnel-in-the-sky displays have good potential of becoming the Primary Flight Display (PFD) of future airplane cockpits. The researchers study the cybernetic aspects in straight trajectory following task while varying the splay line types. Funabiki, Muraoka, Terui, Harigae, and Ono (1999) evaluates the tunnel-in-the-sky display in flight. This approach of decentralized ATM is one of the many other approaches being considered.

These forms of research goes to show that there are numerous possibilities to design the system. However, only a few can be tested and used in a realistic environment.

A-3-3 Centralized and Distributed ATM

Pappas, Tomlin, Lygeros, Godbole, and Sastry (1997) research notes the importance in the availability of technologies such as Global Positioning System (GPS), Datalink communications, ADS-B, Traffic Collision Avoidance System (TCAS) and some high performing computers on board that will benefit the application of decentralized ATM system. A completely centralized system has all safety critical decisions taken centrally and distributed to aircraft. This leads to inefficiencies due to the complexity involved and the limitations of the computational power. Another major problem with complete central control is that there is no tolerance for faults and the response to emergencies may be slow and inefficient. While in the case of completely decentralized system, there may be an increase in the number of conflicts encountered and hence a cost to the efficiency of flight. Researchers also discuss about the degree of decentralization and comments that obtaining an optimal balance is the challenge.

In a research by Krozel, Peters, Bilimoria, Lee, and Mitchell (2001), the system performance characteristics of both centralized and decentralized traffic separation strategies were studied. The performance characteristics were the system stability, efficiency and airspace complexity. Stability of the system is affected adversely when the process of resolving conflicts creates new conflicts with neighboring aircraft, which in turn may cause additional conflicts during subsequent conflict resolution. This domino effect is will be referred to as the knock-on effect. A metric that is discussed by Krozel et al. (2001) is the count of knock-on effects that occur for aircraft that were initially not in a conflicting trajectory. Bilimoria, Grabbe, Sheth, and Lee (2003) also conducted studies regarding the knock-on effects in a 6hr simulation, which concluded that the effects of knock-on conflicts was modest. Efficiency is the measure of the degree to which an aircraft can fly its nominal trajectory. Any deviation from the nominal track costs a penalty. And complexity is another metric used is this research which will give an insight into the effects of stability and efficiency of the airspace. As noted by Laudeman, Shelden, Branstrom, and Brasil (1998); Pawlak, Brinton, Crouch, and Lancaster (1996); Sridhar, Sheth, and Grabbe (1998) although there is no set metric that defines the term airspace complexity metrics, studies indicate the number of aircraft in the airspace is a key factor in determining it. The simulation conducted by Krozel et al. (2001) resulted in relatively low number of loss of separations as compared to the number of conflicts. The results also indicated that there is an increase in the domino effect in decentralized system as compared to centralized system. It also indicates that the system stability is higher in a centralized system. However, on the other hand, the decentralized systems that were tested were much more efficient. Also, as found by J. Hoekstra, Ruigrok, and Van Gent (2001), safety can be maintained even at 3 times the traffic density of the average determined at the year 2000 in a piloted simulation. An interesting comment by the author is that “better a safe chaos, than a dangerous order” which is more or less the essence of FF concept.

A-4 Ecological Interface: Solution Space Diagram

Ecological Interface Design (EID) is an approach in which the design of automation starts with analyzing the environment before directly analyzing the responsibilities of the human. Though automation in aviation has significantly and considerably improved the safety and performance over the years, there are still issues that need attention. One of the major concerns is that an imbalance in distributing responsibilities between a pilot and an automation will lead to a bad overall performance. Simultaneous understand of human behavior and the environment in which they are acting is very crucial to this to bring a balance in the responsibilities of the tasks between the human and the automation while using an intermediate Level of Automation (LOA). In doing research to have a good balance in responsibilities, ecological interfaces were developed. Solution Space Diagram (SSD) is one of such other ecological interfaces researched at the Faculty of Aerospace Engineering, TU Delft.

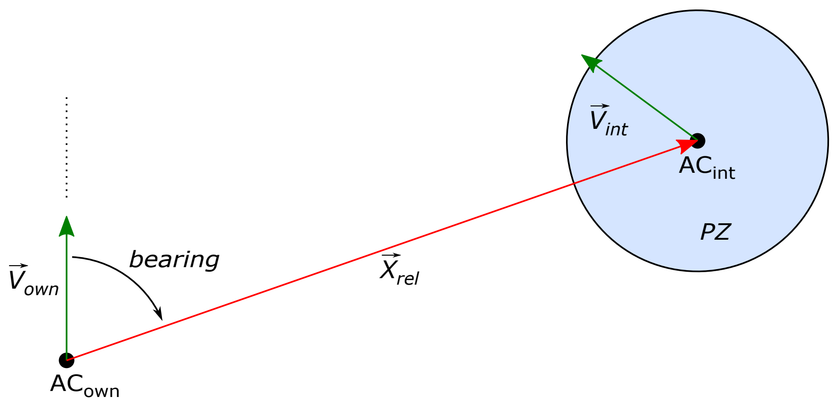


Figure A-3: Derivation of SSD: Situation Overview (adapted from Ellerbroek (2013))

A-4-1 Derivation of Solution Space Diagram

A Solution Space Diagram (SSD), is a representation of relative aircraft velocity vector (of the controlled aircraft with respect to aircraft in vicinity defined by a certain look-ahead time) to depict space of conflicts (known as Forbidden Zone) and space of no conflicts (known as Solution Space). A horizontal SSD (developed from the concept of forbidden areas presents a two-dimensional projection (horizontal) of the traffic constraints, on a relatively traditional cockpit display Van Dam, Mulder, and Van Paassen (2008). For the current study, which is restricted to navigation in the horizontal plane (only visualizing horizontal constraints, and only of obstacles that are on, or close to the own flight level), the derivation of SSD is provided. The following derivation is adopted and optimized to only an extent required in this context. For more information on background researches for the FBZ, the reader is referred to the works of Abdul Rahman, Mulder, and van Paassen (2011); Ellerbroek (2013); Ellerbroek, van Paassen, and Mulder (2011); Van Dam et al. (2008) from which the following derivation is based on.

A case of conflicting aircraft is deliberately chosen. Referring to Figure A-3, AC_{own} and AC_{int} are own aircraft and intruder with velocities $\vec{V}_{own}$ and $\vec{V}_{int}$, headings χ_{own} and χ_{int} respectively. *bearing* is the relative angle of one aircraft with respect to the other (here AC_{int} as seen from AC_{own}). Based on the available information, the following equations can be determined:

$$\vec{V}_{own} = V_{own,gs} \cdot \begin{bmatrix} sin(\chi_{own}) \\ cos(\chi_{own}) \end{bmatrix}$$

$$\vec{V}_{int} = V_{int,gs} \cdot \begin{bmatrix} sin(\chi_{int}) \\ cos(\chi_{int}) \end{bmatrix}$$

$$\vec{x}_{rel} = distance \cdot \begin{bmatrix} sin(bearing) \\ cos(bearing) \end{bmatrix}$$

d_{CPA} and t_{CPA} are calculated as follows (Ellerbroek, 2013) (refer to Figure A-4):

$$t_{CPA} = \frac{\vec{x}_{rel} \cdot \vec{V}_{rel}}{\vec{V}_{rel}^2}$$

$$d_{CPA} = \sqrt{dist^2 - (t_{CPA} \cdot \vec{V}_{rel})^2}$$

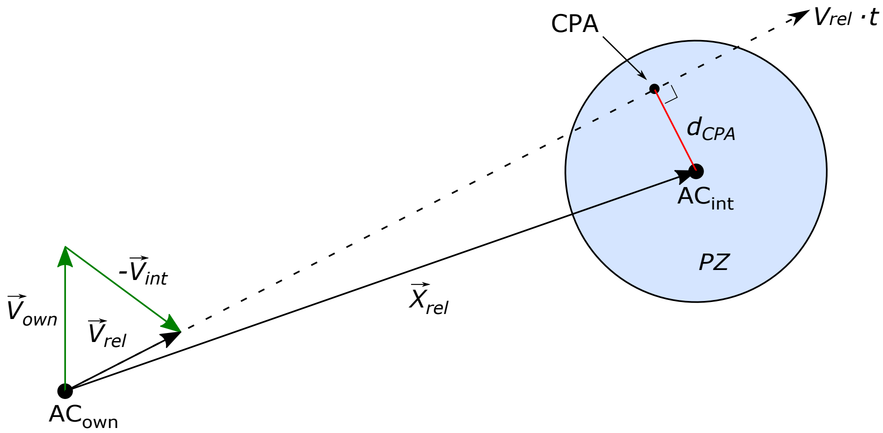


Figure A-4: Derivation of SSD: Calculation of t_{CPA} and d_{CPA} (adapted from Ellerbroek (2013))

As defined in Section A-1, a pair of aircraft are termed as conflicting if the aircraft is within the set t_{LA} and the estimated d_{CPA}< 5 nmi. Referring to Figure A-5, it can be noted the d_{CPA} can occur on either the sides of the AC_{int}'s position depending on the relative velocity

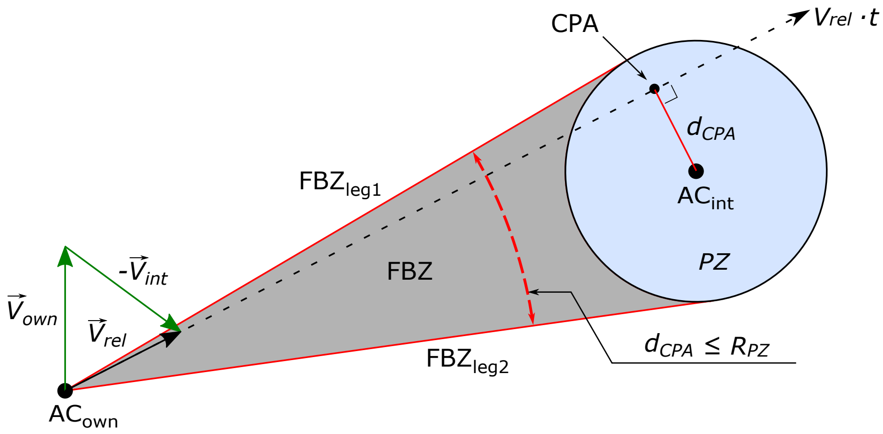


Figure A-5: Derivation of SSD: SSD Legs and FBZ (adapted from Ellerbroek (2013))

vector. If the velocity vectors are drawn at the extreme possibilities for a LOS, 2 tangents to the PZ originating from AC_{own}'s position are seen as a result.

Definition: Forbidden Beam Zone (FBZ): The bounding triangular region between the 2 tangents to PZ of the intruder originating from own aircraft's position is defined as the forbidden zone. And the two tangents will be referred to as Legs of the Forbidden Zone (FBZ legs).

If $\vec{V}_{rel}$ lies inside the FBZ, it is a conflict. In order to make this more intuitive to make use of it in the cockpit, the FBZ is translated along $\vec{V}_{int}$ (see Figure A-6). This essentially brings the perspective of forbidden zone from relative velocity space to own velocity space.

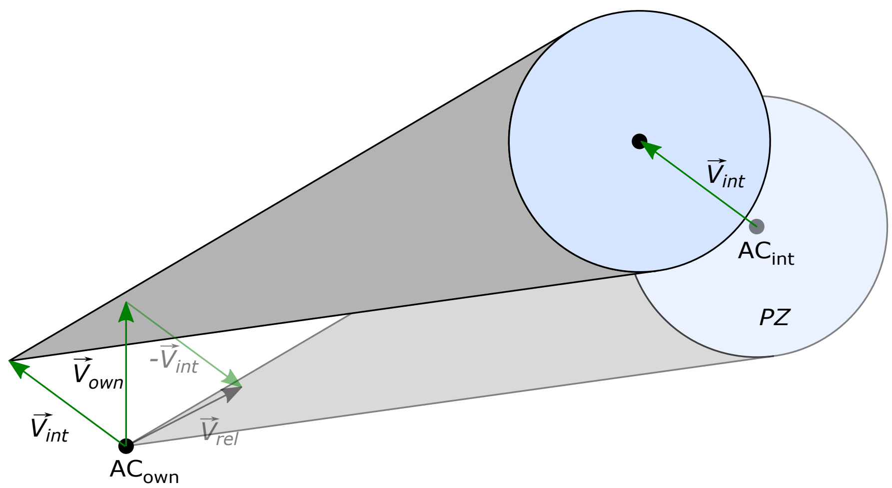
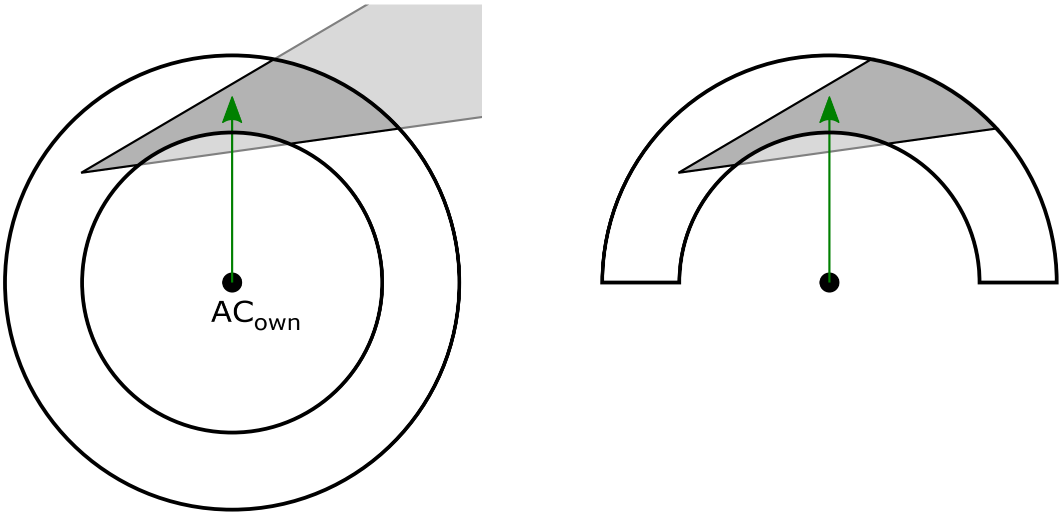


Figure A-6: Derivation of SSD: FBZ in own velocity space (adapted from Ellerbroek (2013))

Now, adding AC_{own}'s velocity bounds provides the SSD diagram that will be used in this research (see Figure A-7).



(a) Full SSD

(b) Half SSD as shown in Navigation Display (ND)

Figure A-7: Derivation of SSD: SSD with Velocity Bounds (adapted from Ellerbroek (2013))

A-4-2 Interpretation and Usage of SSD

The derivation of SSD was discussed in the previous section. The interpretation of SSD and usage , however, is discussed here. The shape, size and appearance of the FBZ depends on the relative velocity, relative track (conflict angle), d_{CPA} and t_{LOS}. The interpretation is fairly straightforward.

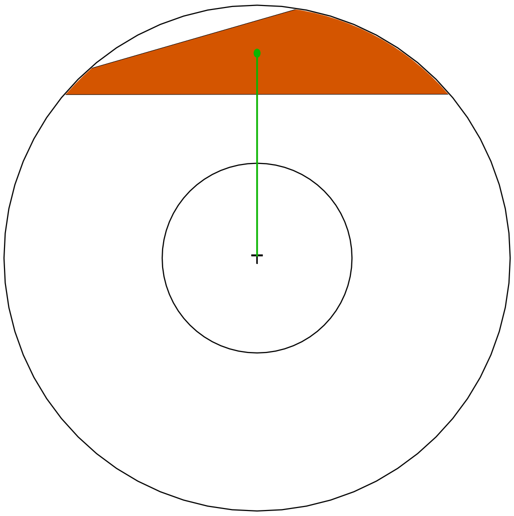
Referring to Figure A-6 and A-7, it can be noted that the displayed FBZ is narrower (the angle between the 2 FBZ legs) when the respective aircraft is far away and gets broader as the distance between the 2 aircraft gets smaller. In other words, the angle between the FBZ legs are inversely proportional to t_{LOS}.

Referring to Figure A-5, it can be seen that the own velocity vector is closer to the FBZ legs as d_{CPA} gets close to separation minima. So, for a given own velocity, the close it is to the angular bisector of the FBZ, the larger is the shortest way to the solution space.

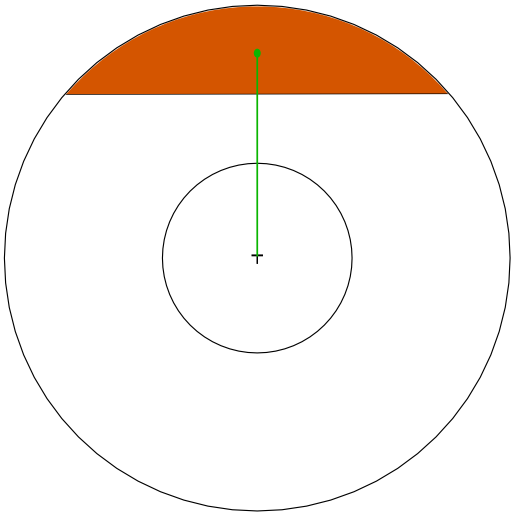
If the velocity space of the observed aircraft is larger than the own aircraft, then the SSD diagram may show ambiguous FBZ. Referring to Figure A-8, it can be seen that the FBZ's point of origin is outside in both the cases. In sub-Figure A-8 (a), the orientation of FBZ is clear. However, in sub-Figure A-8 (b), it raised an ambiguity on the relative track angle.

The parameter t_{LOS}, can be used to communicate the severity of the impending conflict. Severity of conflict may be classified into different color zones as follows:

- Grey: Too far
- Yellow: Closer than Grey
- Orange: Closer than Yellow



(a) A clearly defined FBZ



(b) An unclear FBZ

Figure A-8: Ambiguity in the Interpretation of SSD

- Red: Closer than Orange

Using color to interpret the severity of conflict makes the usage of SSD much more informative (see Figure A-9).

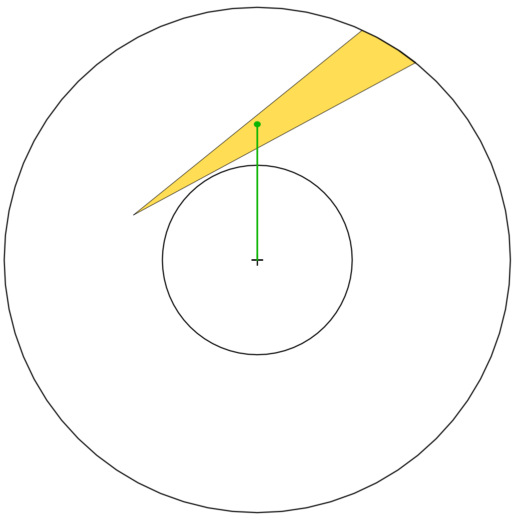


Figure A-9: Coloring in SSD

Research has led to the observation of some interesting properties of SSD. In the solution space (SSD)-based approach, the "solution space" captures the geometrical and kinematic constraints that limit (and therefore, guide) ATCO control actions dEngelbronner, Borst, Ellerbroek, Van Paassen, and Mulder (2015); Hermes, Mulder, Van Paassen, L. Boering, and Huisman (2009); Mercado-Velasco, Mulder, and Van Paassen (2010). Previous studies found high correlations between workload ratings and the area of the available SSD control space. Research is done on several sector complexity measures: Static Density, which equals the number of aircraft flying in a sector, the Dynamic Density as proposed by NASA, and SSD, developed by TU Delft. Comparing these regarding their ability to match the subjective workload ratings obtained in a human-in-the-loop experiment concluded that the solution space-based metric, which requires no tuning or weighing at all, has the highest correlations with subjectively reported workload, and also yields the best workload predictions across different controller groups and sectors Rahman, Borst, van Paassen, and Mulder (2016). This is an important application that will be used in this research to gauge the workload experienced across different conditions of the experiment.

A-5 Coordination Rules

Coordination rules in air traffic conflict resolution are those rules that define what action needs to be taken based on the situation at hand. Depending on whether the system under discussion is centralized or distributed, the responsible authority behind taking this action is either an ATCO or pilot/cockpit system.

A-5-1 Different Rules of Coordination

There are many different rules for coordination in the context of research. The following are a few of them:

1. Rules of the Air (RotA): Rules of the Air was laid out by ICAO in Annex II ICAO (2005). This is also a coordination rule that is in use in present. The following is an excerpt from the said document. Only rules regarding 2 aircraft on approaching head-on, converging, and overtaking situations are presented here.

   The aircraft that has the right-of-way shall maintain its heading and speed.

   (a) An aircraft that is obliged by the following rules to keep out of the way of another shall avoid passing over, under or in front of the other, unless it passes well clear and takes into account the effect of aircraft wake turbulence.

   (b) *Approaching head-on.* When two aircraft are approaching head-on or approximately so and there is danger of collision, each shall alter its heading to the right.

   (c) *Converging.* When two aircraft are converging at approximately the same level, the aircraft that has the other on its right shall give way, except as follows:

      i. power-driven heavier-than-air aircraft shall give way to airships, gliders and balloons;

      ii. airships shall give way to gliders and balloons;

      iii. gliders shall give way to balloons;

iv. power-driven aircraft shall give way to aircraft which are seen to be towing other aircraft or objects.

(d) *Overtaking.* An overtaking aircraft is an aircraft that approaches another from the rear on a line forming an angle of less than 70 degrees with the plane of symmetry of the latter. An aircraft that is being overtaken has the right-of-way and the overtaking aircraft, whether climbing, descending or in horizontal flight, shall keep out of the way of the other aircraft by altering its heading to the right, and no subsequent change in the relative positions of the two aircraft shall absolve the overtaking aircraft from this obligation until it is entirely past and clear.

Pros

- implicit coordination possible
- covers a wide variety of air vehicles and scenarios
- clearly defined in terms of perceiving the situation in the vicinity

Cons

- requires a lot of training to understand exercise this sort of coordination in a diverse air traffic environment
- while the rules are clearly defined for 2 aircraft, the application of the rules when there are more than 2 aircraft becomes ambiguous and sometimes impossible even.

2. Shortest Way Out (SWO): In this coordination rule, the shortest way out of the conflict zone is the advised manoeuvre when an aircraft is in conflict. The resolution may be either change in speed or heading or both. The only criteria is that the resolution takes will be the quickest way out of the conflict at that instant.

Pros

- no complex classification of special cases like RotA
- clearly defined goal makes it easy to understand. Requires relatively less training.
- it is easy to find the quickest way out of the conflict

Cons

- the velocity vector appears to be exactly in the center for conflicts with d_{CPA} close to zero. This creates ambiguity.
- the shortest way out of 2 conflicts may just end up being another conflicts. This creates another form of ambiguity since the only possible way out will be to take a manoeuvre opposite to SWO.
- implicit coordination not always possible, e.g., $d_{CPA} = 0$ situation.

3. Closest right turning: In this coordination rule, when an aircraft is in conflict, the resolution should always be taken in right turning or clockwise turning manner.

   Pros

   - no complex classification of special cases like RotA
   - clearly defined goal makes it easy to understand. Requires relatively less training.
   - it is easy to find the closest right conflict free area

   Cons

   - very inefficient approach. May require unrealistic deviations to resolve conflicts
   - implicit coordination not always possible, e.g., overtaking manoeuvre requires both aircraft to take right.

4. A manoeuvre preference: In this case, when an aircraft is in conflict, only heading changes or only speed changes must be made to resolve the conflict.

   Pros

   - no complex classification of special cases like RotA
   - clearly defined goal makes it easy to understand. Requires relatively less training.
   - it is easy to find the closest right conflict free area

   Cons

   - multiple aircraft conflicts present huge inefficiencies in conflict resolution.
   - implicit coordination not always possible, e.g., conflicts that leave no solution space in allowed manoeuvre space.

A-5-2 Chosen Coordination Rule

It is important to appreciate that none of these coordination rules are perfect. Each of these rules have their own advantages, disadvantages and breaking points. For the purpose of this research, the coordination rule chosen is a combination of different rules discussed above. That is, the actor is allowed to make any move as seen fit by making use of the SSD. This is done to study the human performance without biasing the person with a preset rule of coordination. Though there is a chance that during the simulation someone may pass over exactly on the FBZ angle bisector, but the fact that the manoeuvre is already under way makes it a deliberate conflict that is already resolved.

A-6 Alerting Levels of Severity in the SSD

In previous section, we saw that SSD can be used to communicate the severity of impending conflicts. There are 2 ways this can be done. The first one is by using d_{CPA} and bins of separation distances as proposed by Masalonis and Parasuraman (2003). While using the separation distance bins seems logical, it is quite inefficient since it does not consider the t_{CPA} or t_{LOS} as bin. Having t_{LOS} bins makes the system more efficient since it is time based. The effect of speed is taken into account unlike in separation distance bins.

Rademaker, Theunissen, and Lambregts (2010) discusses the different phases of temporal distance to conflict. Tadema and Theunissen (2009) discusses temporal characteristics of potential conflicts allow prioritization and timing of avoidance manoeuvres.

Tadema, Theinissen, and Kirk (2010) discusses about conflict track bands which indicates if the own aircraft tracks that will result in a violation of the separation based on time. One of the identified positive aspect is the ability to handle more than 1 intruder by drawing more track bands. This is an interesting aspect when that can be applied in this research to visualize the domino effect even before it occurs.

A-7 Multi-Actor Human-in-the-Loop Experiments Design

J. Hoekstra, van Gent, and Groeneweg conducted a HITL experiment involving multiple humans controlled a large number of aircraft in a simulation of a free flight environment J. Hoekstra et al. (2003). This allowed the investigation of the effect human interaction on a micro-scale. The authors discuss that the web experiment showed that it is technologically feasible to run a simulation of free flight over internet. However, an important thing noted was the importance of training and commitment of the participants. A web experiment noted that most of the participants were not committed to attend the entire experiment, while a few of them ignored to participate in the training sessions. It is important to have a good briefing and training. A web experiment will take away the advantage of monitoring the quality of training of the committed participants. Therefore, based on the observations of J. Hoekstra et al., it is decided to have a classroom experiment.

A Human-in-the-loop (HITL) experiment needs to be well designed in order to avoid any confounds from the side of the researcher. This is an important aspect which may ruin the results if not executed properly. Therefore, in order to avoid the confounds from the researcher, the book "*How to Design and Report Experiments*" by Field and Hole (2002) is referred. The reference describes on aspects of experiment planning, design and also on the aspects of analyzing and interpreting collected data.

Appendix B

Multi-Aircraft Conflict Classification (already graded)

THIS APPENDIX IS ALREADY GRADED AS PART OF PRELIMINARY THESIS

The need for a new classification system for multi-aircraft conflicts led to analyzing various methods before arriving at the Conflict-Influence Classification method as presented in the scientific paper (Part I). This appendix discusses all the approaches that were taken, but which failed to meet the criteria stated in Part I. Based on the requirements mentioned, steps are taken towards the creation of a new system of multi-aircraft conflict classification.

B-1 Method 1: Using Resolution Maneuver as a Category

Basis of Classification The first approach taken towards creating a classification system was based on the resulting maneuver when an aircraft in a conflict executes a maneuver based on RotA ICAO (2005).

Key Parameters Used The parameters used as independent variables for this analysis were:

- CPA (varied from 0 to 4.75 nm)
- CA (varied from 0 to 180 degree)
- T_{LOS} (varied from 180 to 300 seconds)
- Aircraft Velocity (V) (varied from 180 to 220 knots)

For simplicity, the following assumptions are made:

- Both aircraft considered are of same type and performance.

- Both aircraft are flying with the same True Air Speed (this will be the speed at which the simulation starts)

Method of Classification Based on the executed maneuver, the levels of classification were:

- *frontside*: indicating a maneuver that resulted in increasing the velocity
- *backside*: indicating a maneuver that resulted in decreasing the velocity
- *left*: indicating a maneuver that resulted in turning towards left
- *right*: indicating a maneuver that resulted in turning towards right

Reason(s) for Discontinuation The analysis was first done for a 2 aircraft scenario. For each case of CPA, CA and T_{LoS}, a resulting maneuver based on ROTA was computed and categorized. When the data was analyzed, a lot of outliers were detected. Upon further investigation, it was found that these outliers existed due to high accuracy of MATLAB®.

However, at this stage a bigger problem started surfacing. The question of how this could be scaled to more than 2 aircraft. The method seemed complicated enough with 2 aircraft. The moment a 3^{rd} aircraft was added to the scenario, the method was no more applicable in a simple manner. This also raised the concern of the applicability of the classification to more than 3 aircraft scenario. After realizing that this method was unrealistic and may be impossible to use for more number of aircraft, the development of this classification was discontinued.

B-2 Method 2: Using Conflict Angles as a Category

Basis of Classification Since the previous method failed to meet the set goals, a new classification system is proposed based on the foundation of ICAO's classification. It was reasonable and simple to consider only conflict angles to define a certain situation. So the basis of the second method was the conflict angles or in this case, relative track angles. The reason the term relative track angles is preferred is because of the fact that not every 3 aircraft scenario has all 3 aircraft in conflict. So, in order to include the aircraft not in conflict, the term relative track angle is used.

Key Parameters Used The key parameters used in this system of classification are:

- Relative Track Angle: The difference in heading angles between given pair of aircraft

The following terms and definitions, which are derived parameters from the relative track angles, is the starting point of this classification.

- T_{con}, is the track angle of the controlled aircraft.
- T_A and T_B, are the track angles of the second and third aircraft respectively.

Method of Classification Conflict angle or the angle between tracks of 2 aircraft is chosen between 0 and 180 degree. The reason for the limit is simply because, anything beyond 180 degree is simply a mirrored scenario between 0 and 180 degrees.

With that, we define an angular bisector as follows:

$$b_{A\_con} = \frac{T_A - T_{con}}{2}$$

Reason(s) for Discontinuation: This analysis is somewhat slightly complicated with just 3 aircraft. When fourth aircraft is introduced for the classification, this method of classification fails due to its complexity. It become unrealistic and highly complicated for anything more than 3 aircraft. The reasons to discontinue this method already were sufficient enough. Hence, next new method was sought out.

B-3 Method 3: Using the number of aircraft

This method is described as part of the scientific article in Part I.

Appendix C

Design of Air Traffic Scenarios

The traffic scenarios C_3, C_3I_3, C_5 and C_5I_3 that were used in the experiment are presented in this appendix. Figure C-1, Figure C-2, Figure C-3 and Figure C-4 present the scenarios C_3, C_3I_3, C_5 and C_5I_3 respectively.

For each pair of scenarios (C_3 - C_3I_3 and C_5 - C_5I_3), the conflict only scenarios were designed first. The aircraft were designed to start with a conflict or to get involved in a conflict without any change of state. The scenarios were simulated in *BlueSky* by varying the speed, heading and the position parameters of each aircraft. The interaction of each aircraft (in the velocity space) and the possibilities of maneuvers were taken into account while varying these parameters. Once the conflict scenario was designed and simulated, influence aircraft were added individually. The influence aircraft were placed such that, the resolution maneuvers from conflict scenarios would create a conflict with the influence aircraft. Some influence aircraft were placed in such a way that they never got involved, but had the chances of being involved.

C-1 Scenario C_3

Figure C-1 shows the scenario visualization. Table C-1 shows the coordinates, orientation and the velocity of each of the aircraft. In this scenario, (AC-1, AC-2) and (Ac-1, AC-3) pair are involved in a conflict. A global resolution maneuver by AC-1 can resolve all the conflicts. While alternatively, a sequential resolution involving all three aircraft also resolves the conflicts.

C-2 Scenario C_3I_3

Figure C-2 shows the scenario visualization. Table C-2 shows the coordinates, orientation and the velocity of each of the aircraft. The influence aircraft are now added to C_3.

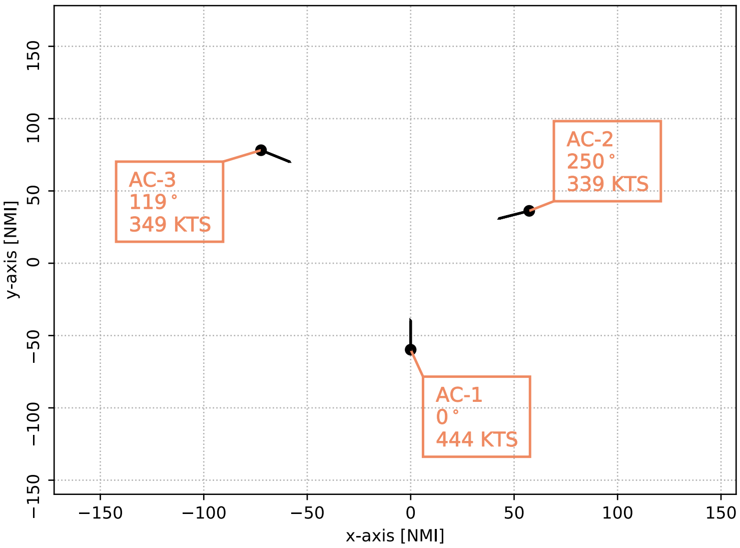


Figure C-1: Conflict Only Scenario C_3

Table C-1: Coordinates for C3

Aircraft ID	AC-1	AC-2	AC-3
Position X [NMI]	0.0	57.309	-72.329
Position Y [NMI]	-59.768	36.223	78.157
Heading [Deg]	0.0	250.0	120.0
Velocity [KTS]	445.0	340.0	350.0

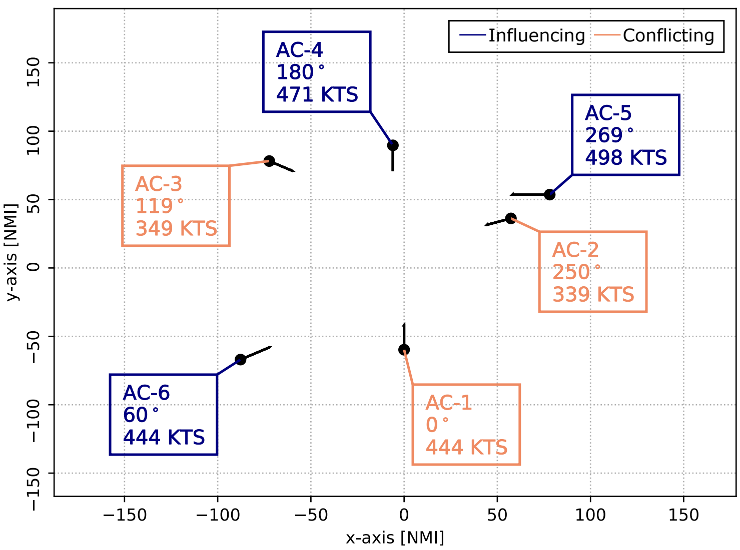


Figure C-2: Conflict Only Scenario C_3I_3

Table C-2: Coordinates for C3I3

Aircraft ID	AC-1	AC-2	AC-3	AC-4	AC-5	AC-6
Position X [NMI]	0.0	57.309	-72.329	-6.006	78.133	-87.76
Position Y [NMI]	-59.768	36.223	78.157	89.655	53.628	-66.993
Heading [Deg]	0.0	250.0	120.0	180.0	270.0	60.0
Velocity [KTS]	445.0	340.0	350.0	472.0	499.0	445.0

C-3 Scenario C_5

Figure C-3 shows the scenario visualization. Table C-3 shows the coordinates, orientation and the velocity of each of the aircraft. In this scenario, there are aircraft involved in multiple conflicts with each other. Small resolutions by each aircraft was observed to resolve all the conflicts.

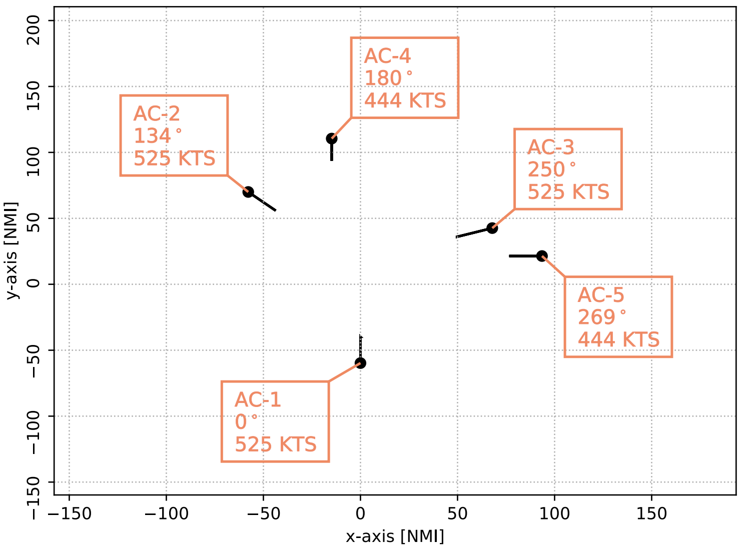


Figure C-3: Conflict Only Scenario C_5

Table C-3: Coordinates for C5

Aircraft ID	AC-1	AC-2	AC-3	AC-4	AC-5
Position X [NMI]	0.0	-57.8	67.891	-14.813	93.506
Position Y [NMI]	-59.765	70.004	42.6	110.49	21.419
Heading [Deg]	0.0	135.0	250.0	180.0	270.0
Velocity [KTS]	526.0	526.0	526.0	445.0	445.0

C-4 Scenario C_5I_3

Figure C-4 shows the scenario visualization. Table C-4 shows the coordinates, orientation and the velocity of each of the aircraft. In this scenario, adding AC-6 and AC-7 to scenario C_5 gave less room to maneuver for some aircraft. Deliberate conflicts may be observed in this kind of a scenario. This is due because, this situation presents a solution which may be located on the opposite side of the SSD. AC-8 is just placed in such a way that it cleanly passes between AC-5 and AC-7. Although no maneuver is expected, an increased sense of factor of safety may lead to a maneuver resulting from AC-8.

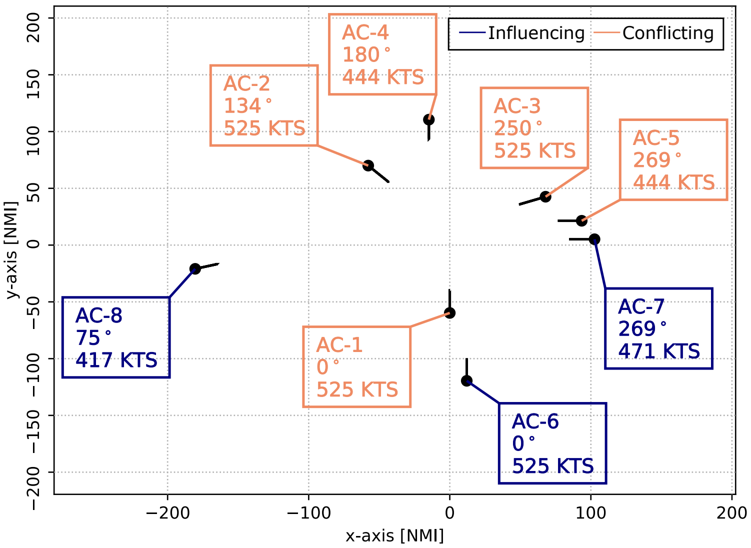


Figure C-4: Conflict Only Scenario C_5I_3

Table C-4: Coordinates for C5I3

Aircraft ID	AC-1	AC-2	AC-3	AC-4	AC-5	AC-6	AC-7	AC-8
Position X [NMI]	0.0	-57.8	67.891	-14.813	93.506	12.03	102.593	-180.459
Position Y [NMI]	-59.765	70.004	42.6	110.49	21.419	-119.527	5.161	-20.921
Heading [Deg]	0.0	135.0	250.0	180.0	270.0	0.0	270.0	75.0
Velocity [KTS]	526.0	526.0	526.0	445.0	445.0	526.0	472.0	417.0

Appendix D

Experiment Documents

This appendix presents all the documents used for conducting the experiment in the order they were used in the research as follows:

1. Approval from the Human Research Ethics Committee (Section D-1)
2. Informed consent form (Section D-2)
3. Briefing document (Section D-3)
4. Experiment briefing presentation (Section D-4)
5. Experiment checklist (Section D-5)
6. Post-run questionnaire (Section D-6)
7. Post-experiment questionnaire (Section D-7)

D-1 Approval from the Human Research Ethics Committee

In order to conduct a human-in-the-loop experiment, the research proposal first needs to be approved by a human research ethics committee. An application was made to the Human Research Ethics Committee at Delft University of Technology and the approval document is attached in the following page.

Date 13-07-2017
Contact person Ir. J.B.J. Groot Kormelink, secretary HREC
Telephone +31 152783260
E-mail j.b.j.grootkormelink@tudelft.nl

Human Research Ethics Committee
TU Delft
(http://hrec.tudelft.nl/)

Visiting address
Jaffalaan 5 (building 31)
2628 BX Delft

Postal address
P.O. Box 5015 2600 GA Delft
The Netherlands

Ethics Approval Application: Multi-Actor Self Separation in Complex Airspace Environments
Applicant: Tegginamani Shiva Kumar, Siddarth

Dear Siddarth Tegginamani Shiva Kumar,

It is a pleasure to inform you that your application mentioned above has been approved.

Good luck with your research!

Sincerely,

Prof. Dr. Sabine Roeser
Chair Human Research Ethics Committee TU Delft

Prof.dr. Sabine Roeser
TU Delft
Head of the Ethics and Philosophy of Technology Section
Department of Values, Technology, and Innovation
Faculty of Technology, Policy and Management
Jaffalaan 5
2628 BX Delft
The Netherlands
+31 (0) 15 2788779
S.Roeser@tudelft.nl
www.tbm.tudelft.nl/sroeser

D-2 Informed Consent Form

The participants were informed of their rights as a participant. To get an acknowledgement, a form of informed consent was asked to be filled and signed by every participant. The form used is attached in the following page.

Thesis Experiment
Consent & Participant Data Form

S. Tegginamani Shiva Kumar

You have been asked to participate in an experiment conducted by Siddarth Tegginamani Shiva Kumar (researcher) in partnership with Clark Borst (supervisor) and Joost Ellerbroek (supervisor). Prior to commencement you are requested to answer the questions presented below. Furthermore, you are kindly asked to read and understand the briefing document. Finally, please provide your signature below to indicate that you agree to participate in this experiment. Signing this form does not annul the responsibilities of the researcher and Delft University of Technology towards you as a participant. Any data you write here will be kept confidential, only the researcher has insight in personal data. You agree that anonymized data may be published.

First Name	
Last Name	
Age	
Gender	

I hereby confirm that I have read the experiment briefing. Also, I affirm that I understand the experiment instructions, and I declare that I voluntarily participate in this experiment. Finally, I have been informed of my right to withdraw from participating in the experiment at any time without having to provide any reason.

Date: ________________ Signature: ____________________

D-3 Briefing Document

A briefing document which was sent out to the participants two days before the experiment. This document was made with the intent to introduce the participants with the interfaces used in the the experiment and about flying strategies of pilots. The document used is attached in the following page.

Multi-Actor Self-Separation in Complex Airspace Environments

Briefing hand-out

This document will give you necessary and sufficient information that is required for the experiment. Please read this before you arrive to participate in the experiment.

Images are attached to give better understanding. Please refer to them as and when they are mentioned.

1. **Role of Pilots:**

Commercial airlines try to reduce flying costs as much as possible. To this end, the pilots are obliged to follow the strategy that an airline employs to make the flight plan as efficient as possible while complying to the safety critical aspects. Once the flight plan is set, the pilots follow the predetermined waypoints to reach their destination.

Flight planning is the process of producing a flight plan to describe a proposed flight from source to destination. Flight plans involve 2 safety critical aspects: fuel consumption calculation to ensure sufficient fuel is available to reach the destination; compliance with Air Traffic Control to minimize mid-air collision.

Accurate data on the payload on that flight, weather forecasts and data on restricted airspaces are required to come up with a flight plan. A flight plan when finished, among other information, has a complete route plan indicating all the waypoints to be followed by the aircraft.

2. **Modern Cockpit (see “Image 1 - Modern Glass Cockpit”):**

Modern (Glass) Cockpit is a terminology used to describe the cockpit of modern aircraft. Previously, the cockpit had a very complex set of analogue instruments that had 1 function only. With modern glass cockpit, multiple functions were integrated into a single electronic display. This has reduced a great number of instruments inside the cockpit.

3. **Navigation Display (see “Image 2 - Navigation Display”):**

Navigation Display is a display in the modern glass cockpit that provides information on aircraft’s lateral situation. The information indicated, among other things, include the path to follow, ground speed, true airspeed, heading angle, way point information, weather information. Pilots use this to assess the present situation before commanding the autopilot.

4. **Mode Control Panel (see “Image 3 - Mode Control Panel”):**

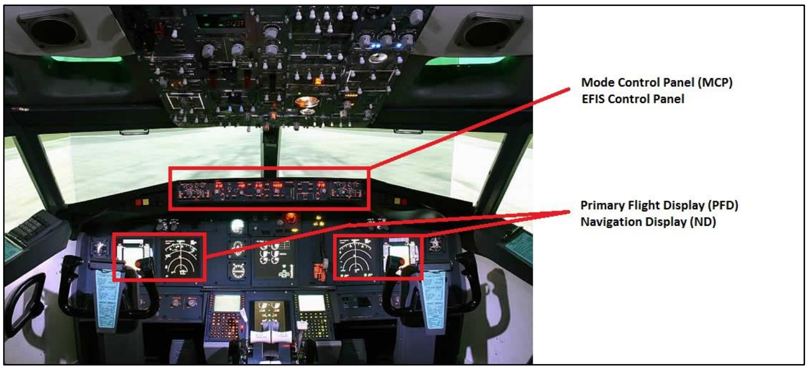
Mode Control Panel is a panel in the cockpit that controls the autopilot of the aircraft. Pilots use this to input their command to control their aircraft. There are several autopilot modes. Among others, few are, altitude hold mode which commands the aircraft to remain at or manoeuvre to the specified altitude, heading mode which commands the aircraft to remain at or manoeuvre to the specified heading.

5. **EFIS Control Panel (See “Image 4 - EFIS Control Panel”):**

Electronic Flight Instrument System, in short EFIS (ee-fis) panel, is a collective term to describe the modern electronic cockpit system. EFIS Control Panel is a cockpit instrument that controls the way in which information is displayed on the Navigation Display and Primary Flight Display (another display in a modern cockpit). For example, this panel, enables to view weather information, control the maximum range covered by the display, etc...

The information provided in this document will be dealt again for the purpose of clarity during the experiment. During the experiment, you will also be told what exactly you are allowed to control and how you can do it in order to meet the objective.

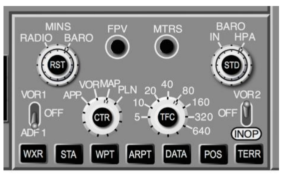
End of the document.



Attachment 1: Modern Glass Cockpit

Attachment 2: Navigation Display

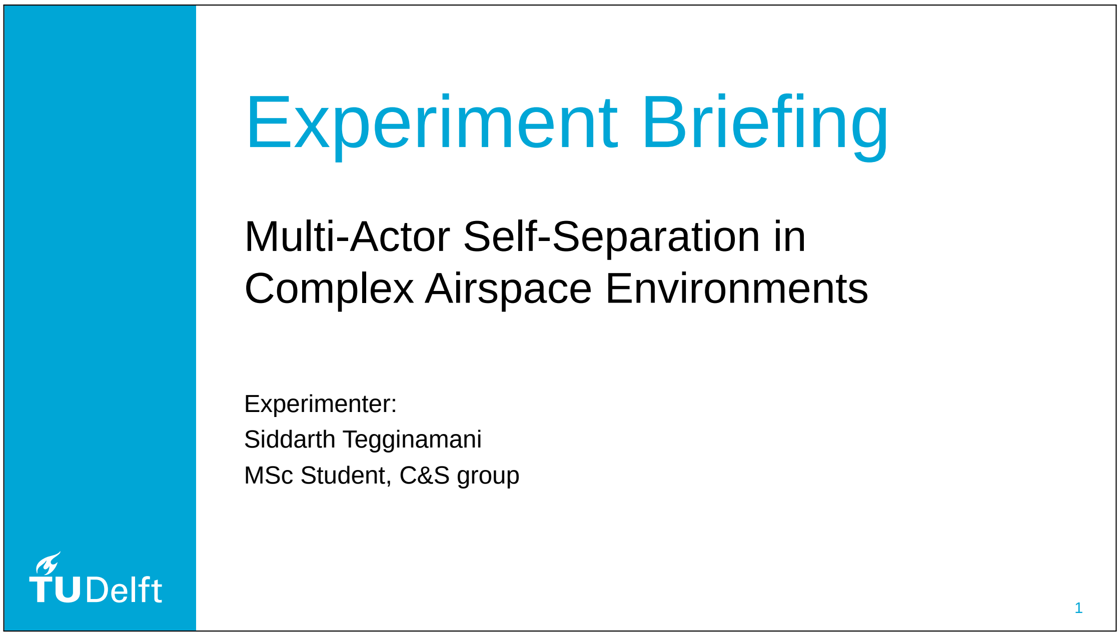
Attachment 3: Mode Control Panel

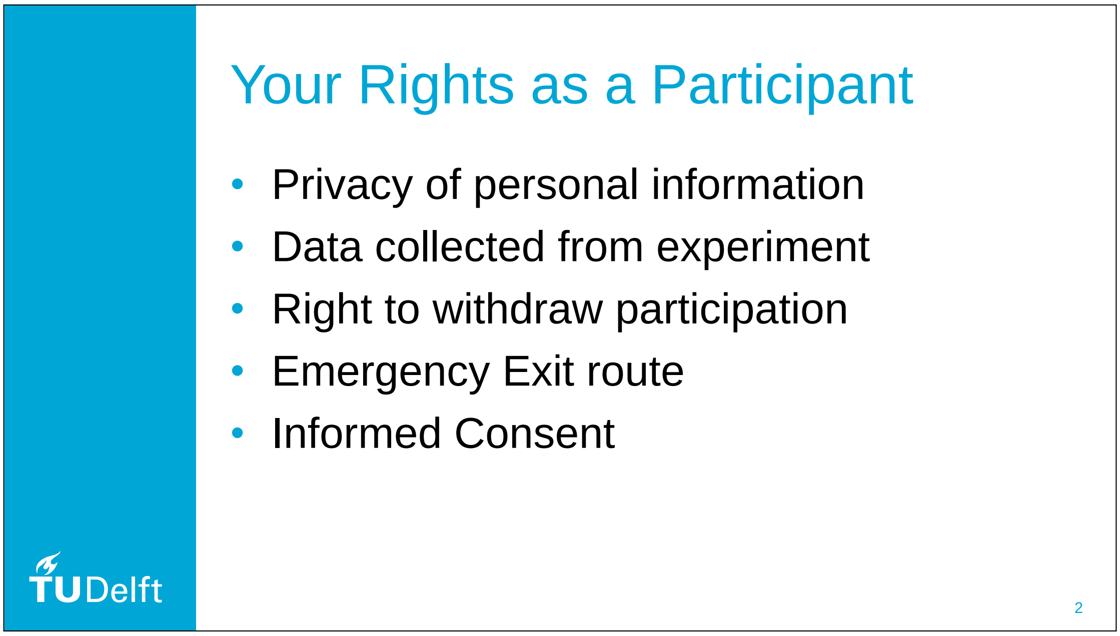


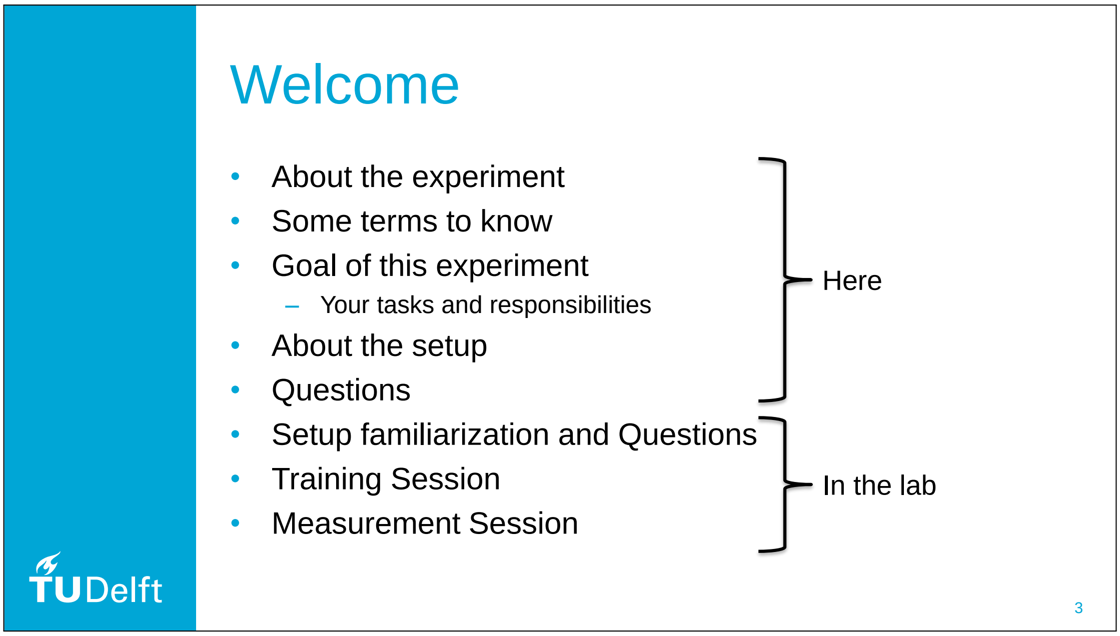
Attachment 4: EFIS Control Panel

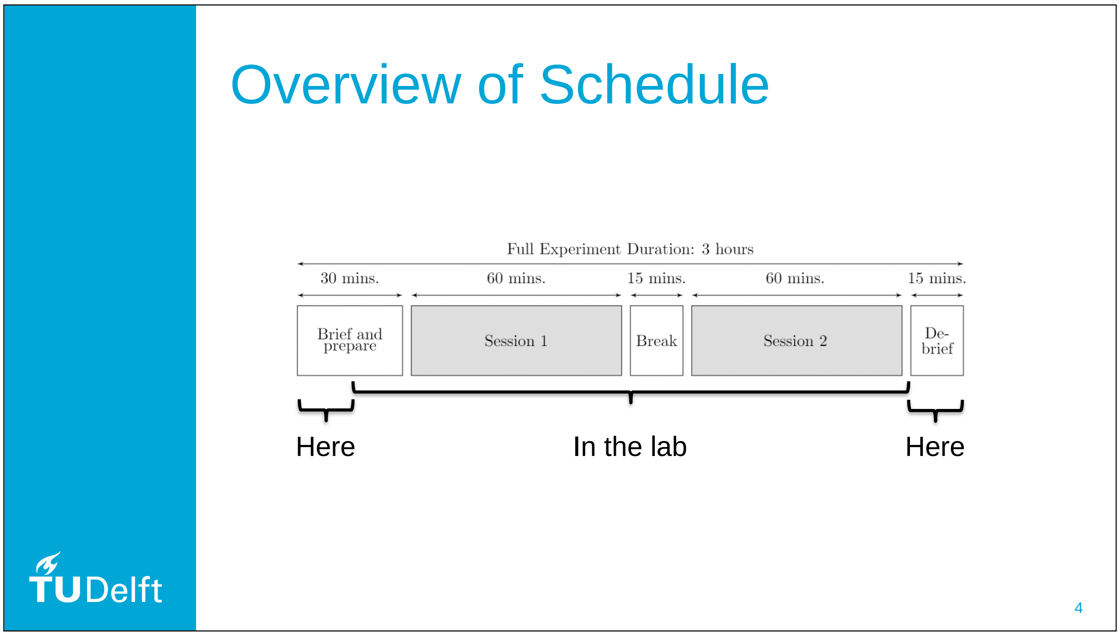
D-4 Briefing Presentation

On the day of the experiment, the participants were briefed for the first 45 minutes. The briefing included a PowerPoint presentation and two supporting videos. The videos (approximately 15 seconds each) were used to demonstrate the conflicts, intrusions and conflict resolutions. The briefing presentation is attached in the following pages.


Experiment Briefing
Multi-Actor Self-Separation in Complex Airspace Environments
Experimenter:
Siddarth Tegginamani
MSc Student, C&S group
TU Delft
1

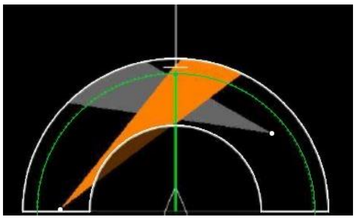

Your Rights as a Participant
Privacy of personal information
Data collected from experiment
Right to withdraw participation
Emergency Exit route
Informed Consent
TU Delft
2


Welcome
About the experiment
Some terms to know
Goal of this experiment
Your tasks and responsibilities
About the setup
Questions
Setup familiarization and Questions
Training Session
Measurement Session
Here
In the lab
TU Delft
3


Overview of Schedule
Full Experiment Duration: 3 hours
30 mins.
60 mins.
15 mins.
60 mins.
15 mins.
Brief and prepare
Session 1
Break
Session 2
De-brief
Here
In the lab
Here
TU Delft
4

About this Experiment

A multiplayer simulation to test a display being developed by the department.

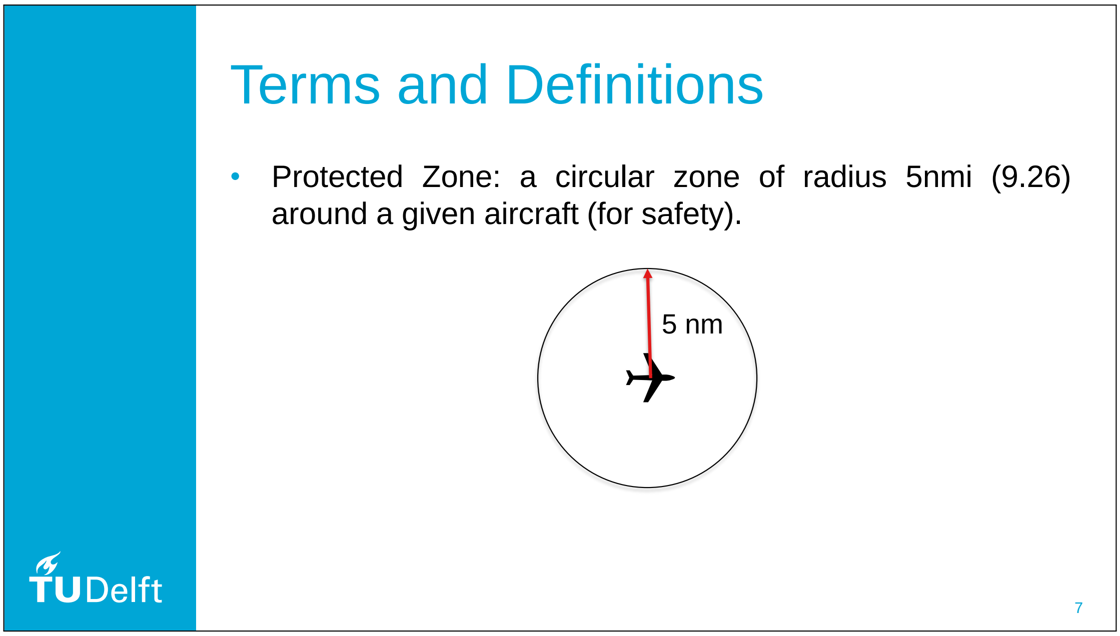


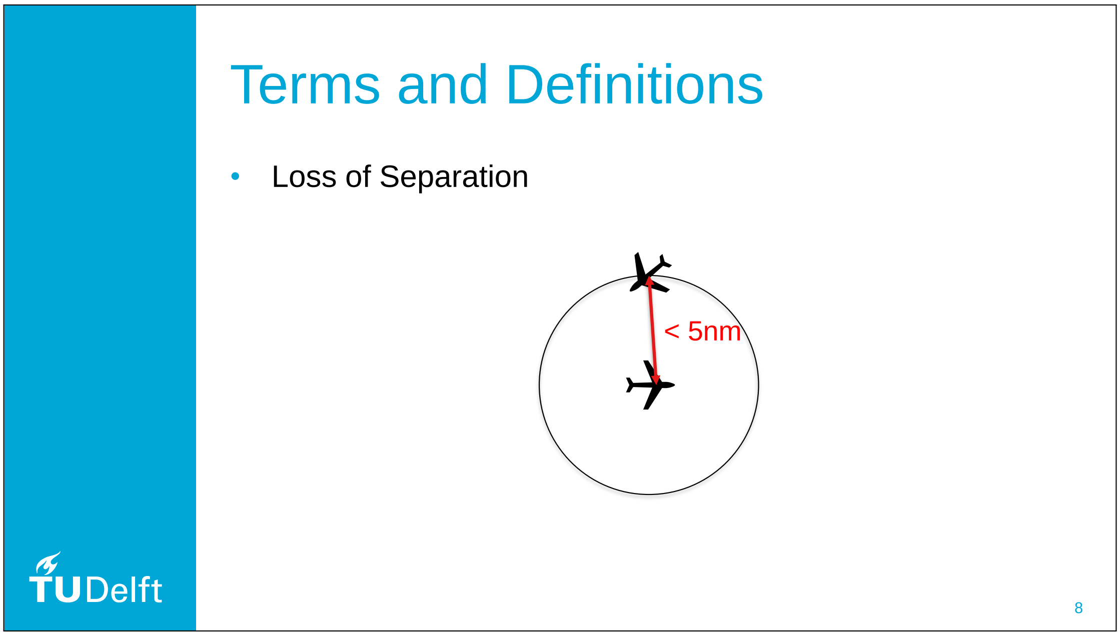
5

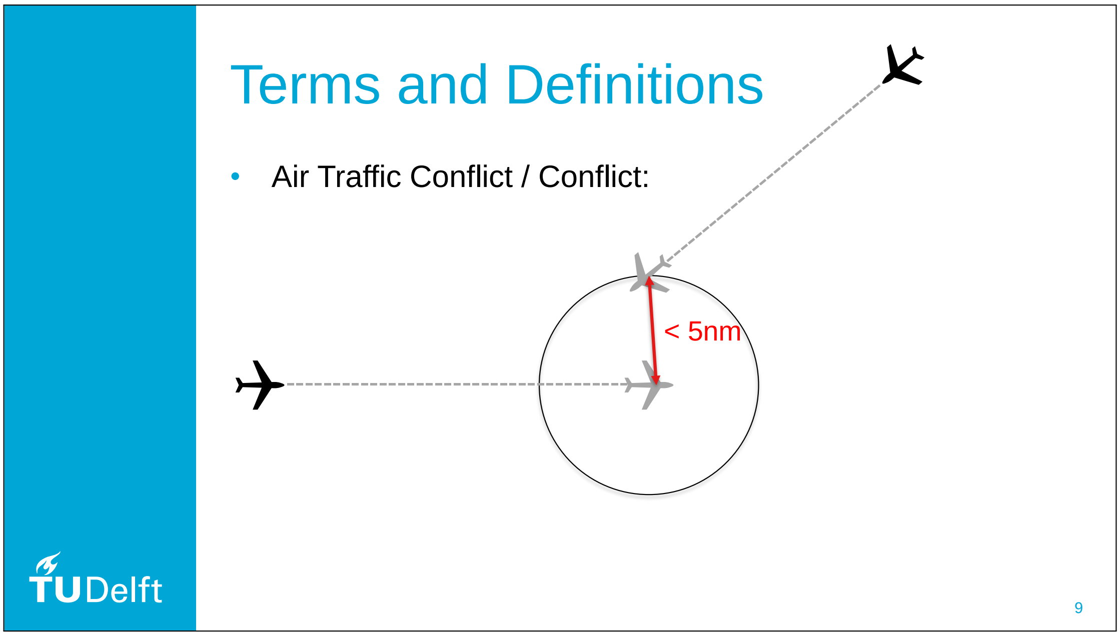
Task overview

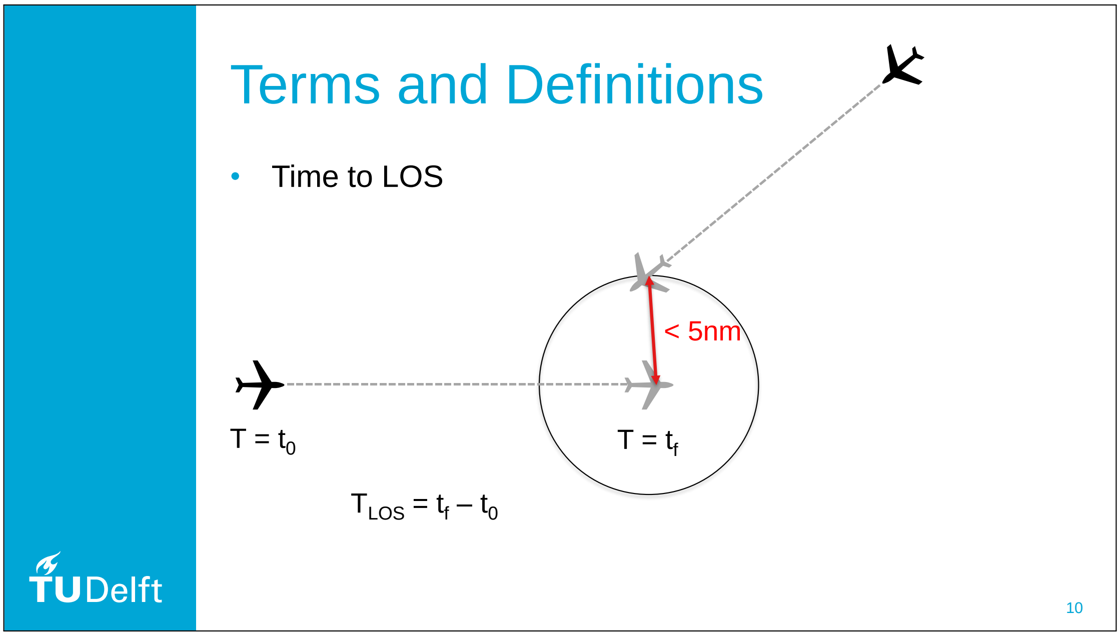
- Listen to my instructions on simulation start and stop
- Perform simulation task
- Answer Questionnaire

6


Terms and Definitions
• Protected Zone: a circular zone of radius 5nmi (9.26) around a given aircraft (for safety).
5 nm
TUDelft
7


Terms and Definitions
• Loss of Separation
< 5nm
TUDelft
8


Terms and Definitions
• Air Traffic Conflict / Conflict:
< 5nm
TU Delft
9


Terms and Definitions
• Time to LOS
< 5nm
T = t0
T = tf
TLOS = tf – t0
TU Delft
10

LOS Movie

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11

Any questions so far?

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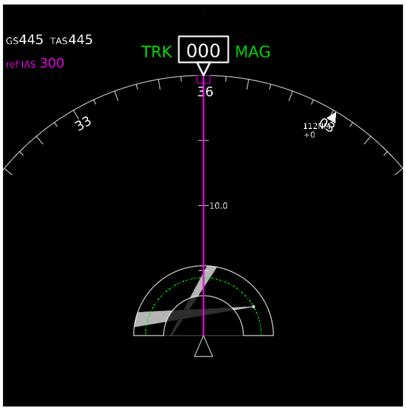
Goal

Fly your aircraft on the indicated path with reference speed while avoiding any Loss of Separation



TUDelft

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Simulation task

1. Simulation start: “The simulation starts in 3.. 2.. 1.. now”.
2. Once the simulation starts,
   1. Your goal is to traverse the assigned path without having any LoS
   2. If you encounter or predict an encounter of conflict, then
      - Either change only heading
      - OR change only speed
      - OR change both speed and heading
      - OR change neither speed nor heading
   3. Return to assigned path
3. When the simulation ends
   1. Fill in the presented questionnaire
   2. Wait for the next simulation start announcement.

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Questionnaire

1. 1 after each run
2. 1 at the end of the experiment

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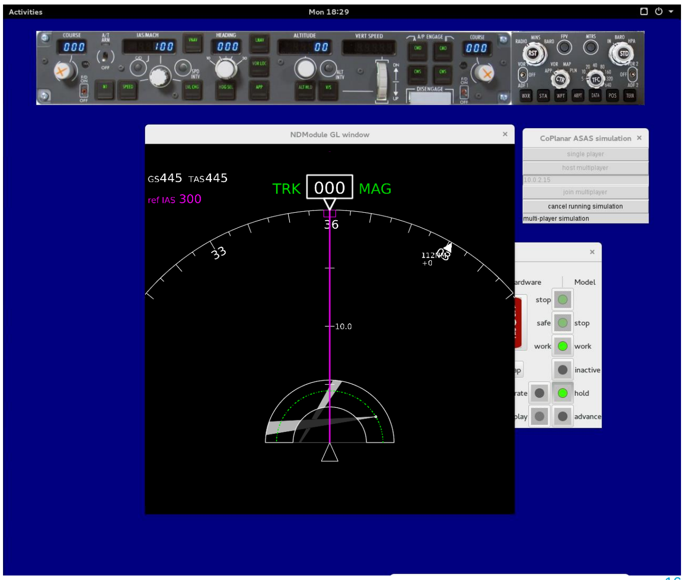
Setup



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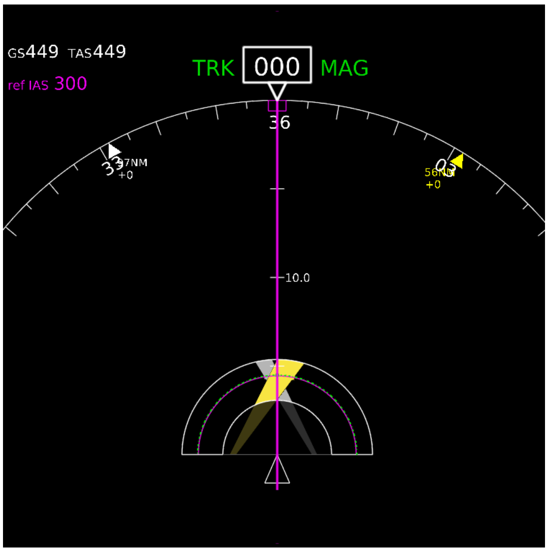
About ND



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MCP and EFIS control panel

- IAS (Indicated Airspeed)
- Heading
- ND Range (20 nmi)

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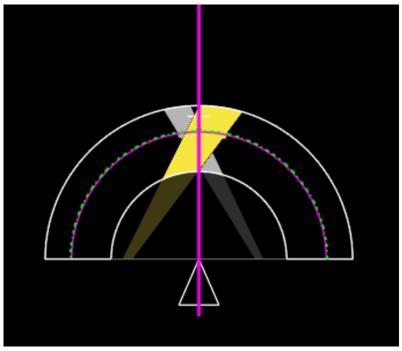
About SSD

A visual representation of the lateral situation in the vicinity of the aircraft



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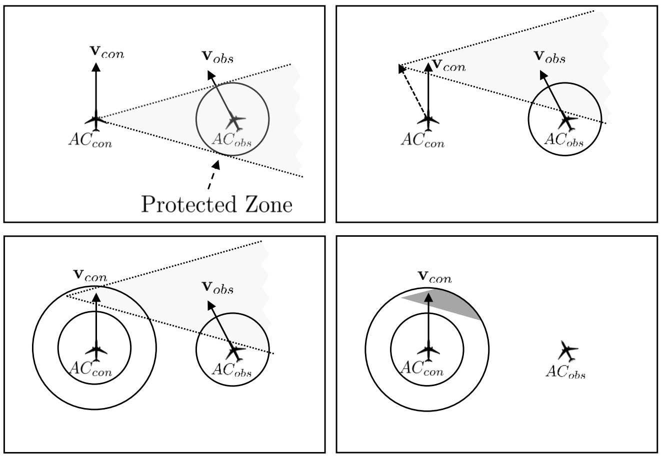
2D Solution Space



Adapted from (Abdul Rahman, 2014)

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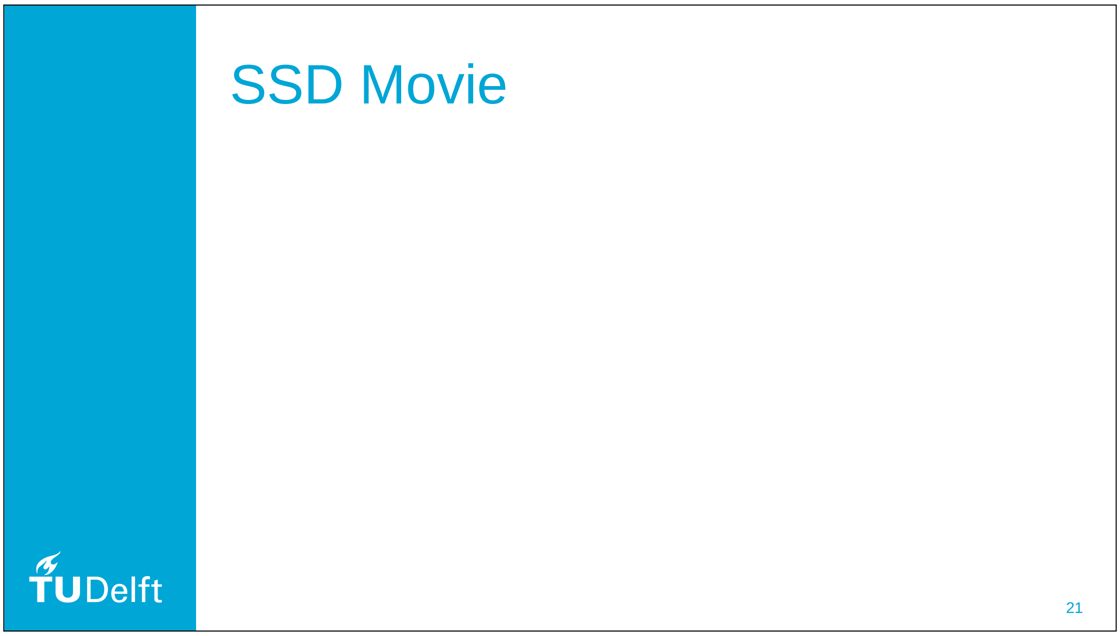
SSD Movie
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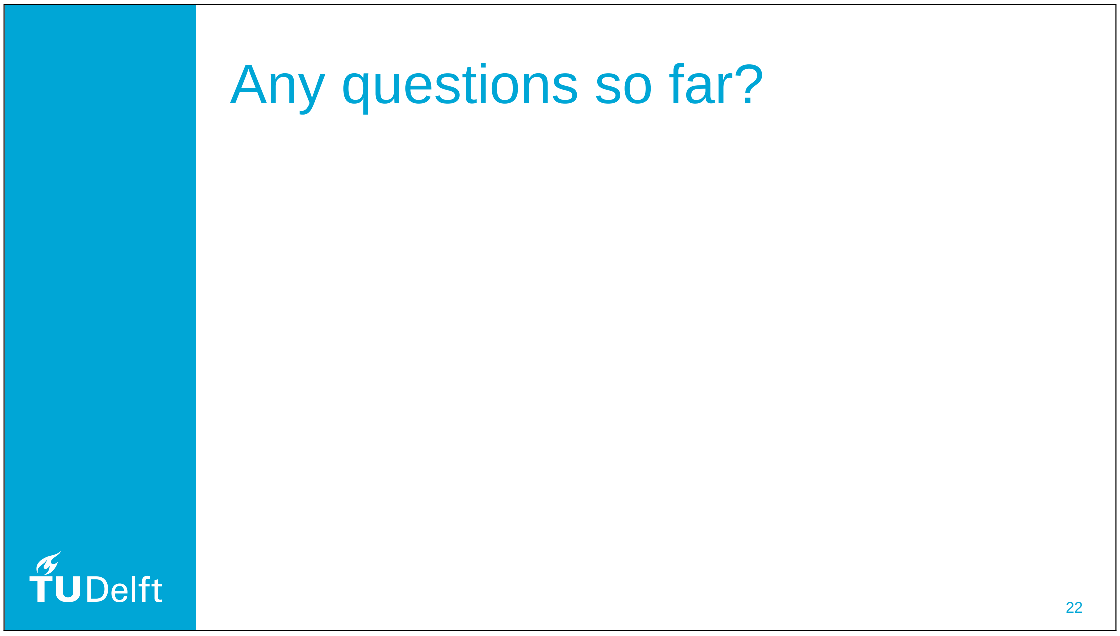
Any questions so far?
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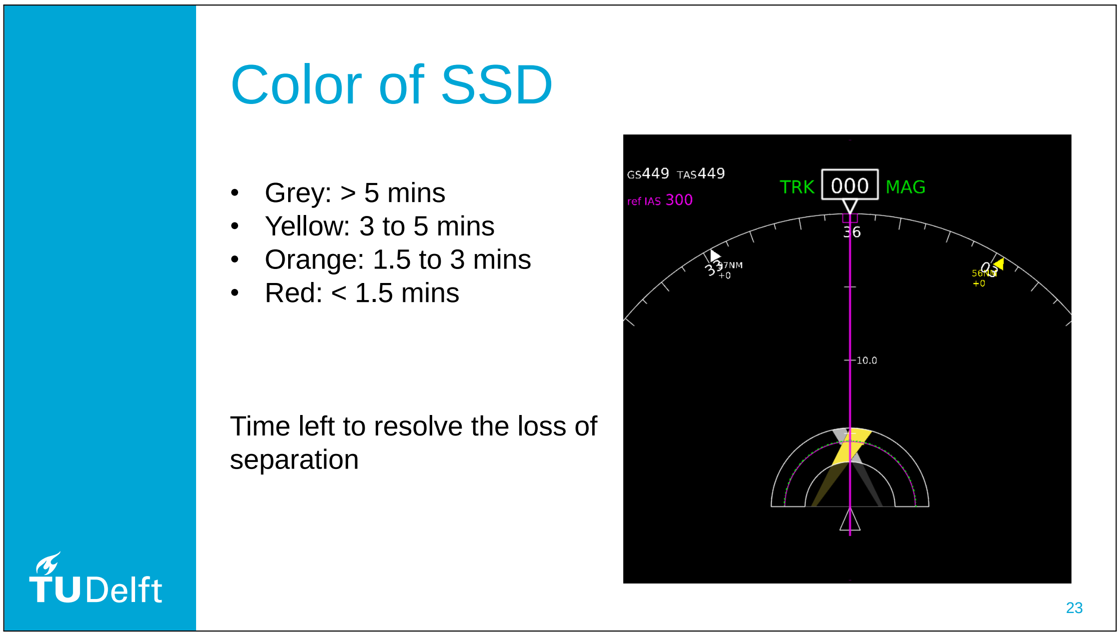
Color of SSD
• Grey: > 5 mins
• Yellow: 3 to 5 mins
• Orange: 1.5 to 3 mins
• Red: < 1.5 mins
Time left to resolve the loss of separation
GS449 TAS449
ref IAS 300
TRK 000 MAG
36
10.0
TU Delft
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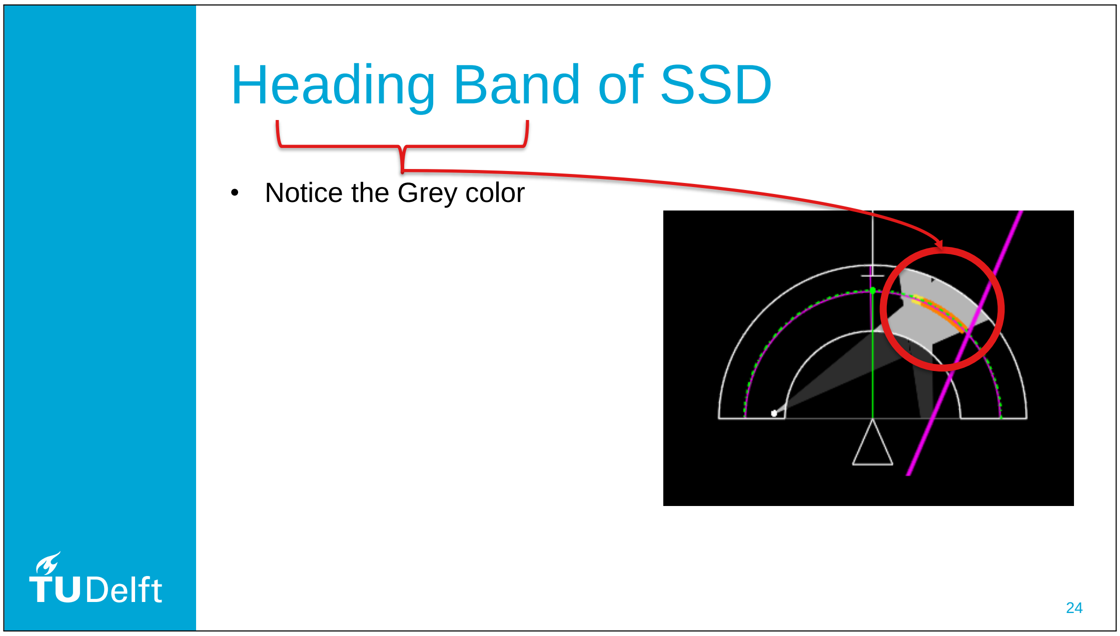
Heading Band of SSD
• Notice the Grey color
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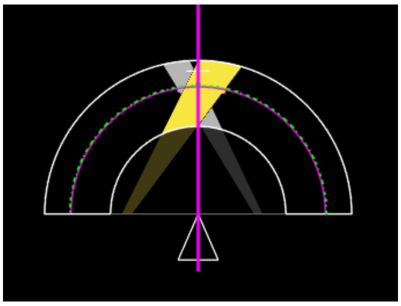
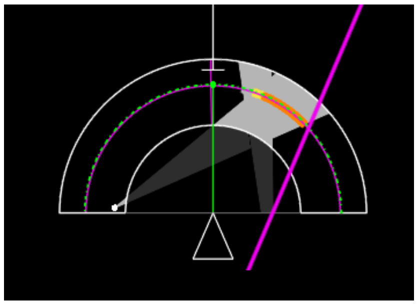
Color Interpretation

1. Color change is interpretation of time left
2. Do not treat a conflict detection as a Loss of Separation

25

How to Avoid Conflict





1. Forbidden zone and Occurrence of conflict
2. Own Velocity Vector
3. Not exactly on the line

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Good practices

1. Think like a pilot. Be like a pilot.
   - Be patient and analyze the situation first
   - Avoid unnecessary maneuvers.
   - Make a maneuver only if it is necessary. Be efficient.
   - Return to initial path and return to initial speed as well.
   - Slow and steady maneuvers
   - Consider intruder's response
2. Utilize the coloring to strategize your route
3. Making a justifiable maneuver

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Bad practices

1. Directly resolving a conflict without thinking of a strategy
2. Initiating very quick and sudden maneuvers. Pilots don't do that. Neither should you.
3. Not making use of the Solution Space
4. Using ND range to eye ball the scenario

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Information to use

- Any information you use should be only from display that is assigned to you.
- Direct communication with any other participant is not allowed either during the experiment session or during the break.

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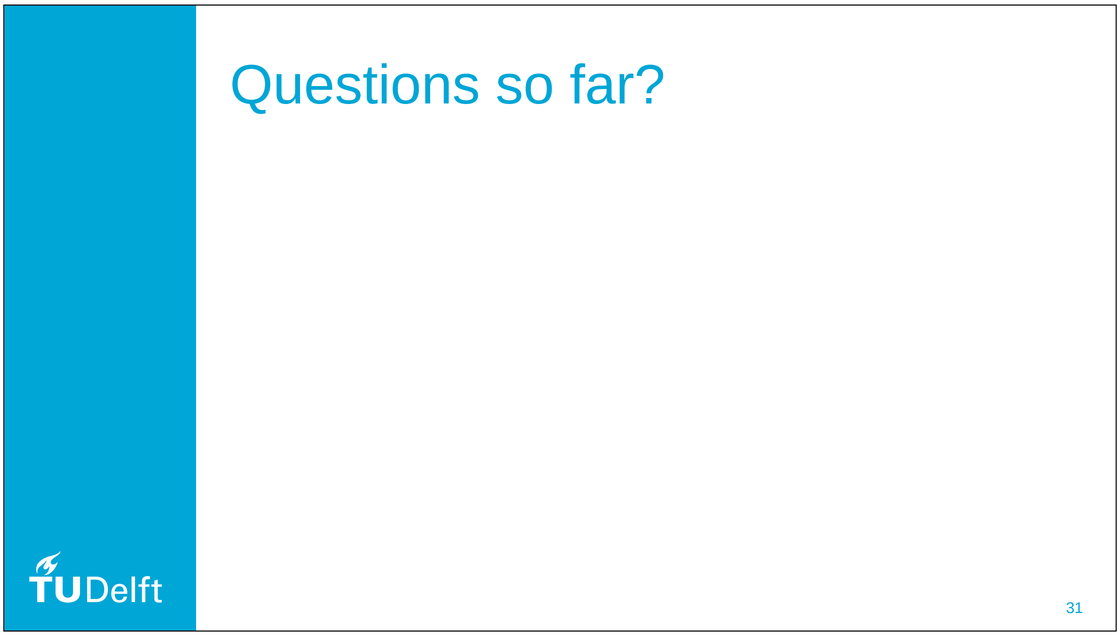
Summary

- Follow the indicated path and maintain reference speed
- If you make a maneuver, make sure your return to your initial path and speed
- Make use of the coloring:
  - Grey => 5 mins
  - Yellow => 3 to 5 mins
  - Orange => 1.5 to 3 mins
  - Red => 1.5 mins
- Answer the questionnaire

30


Questions so far?
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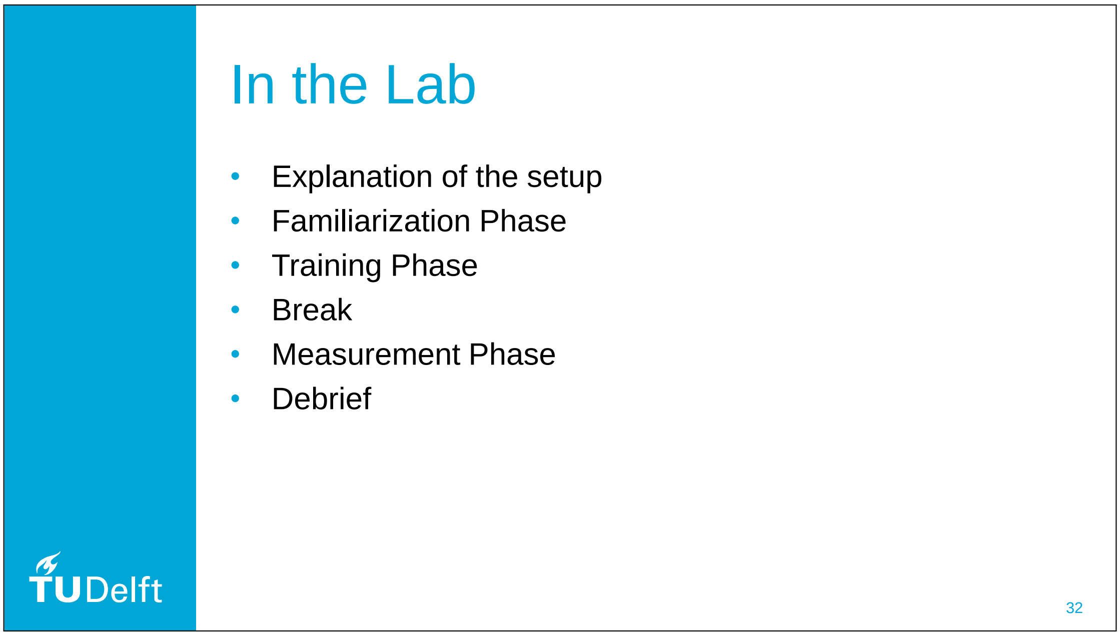
In the Lab
Explanation of the setup
Familiarization Phase
Training Phase
Break
Measurement Phase
Debrief
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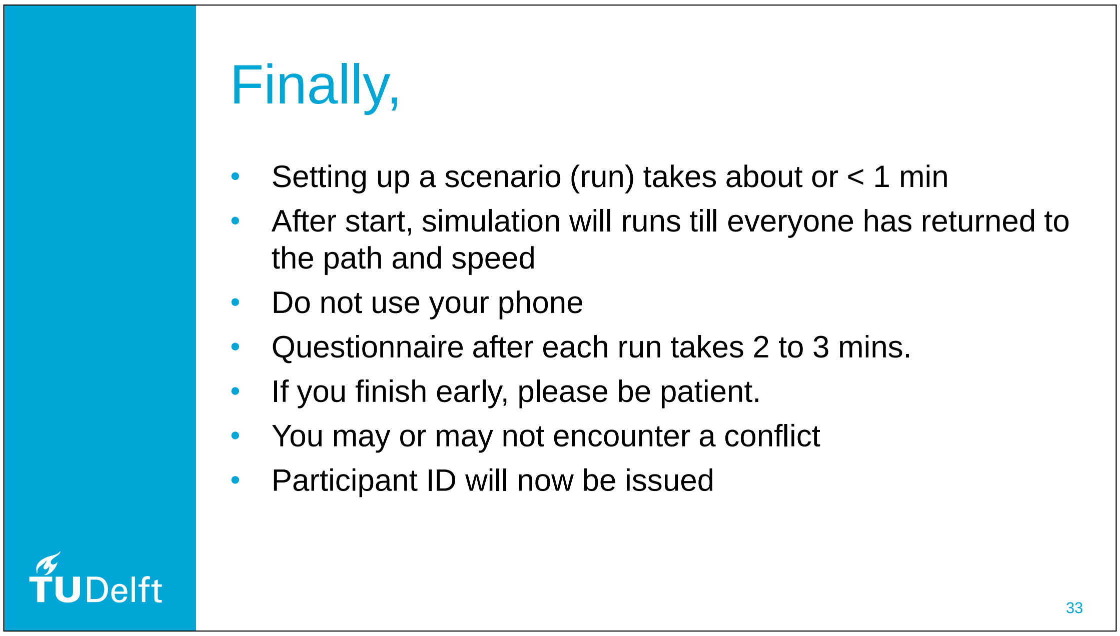
Finally,
Setting up a scenario (run) takes about or < 1 min
After start, simulation will runs till everyone has returned to the path and speed
Do not use your phone
Questionnaire after each run takes 2 to 3 mins.
If you finish early, please be patient.
You may or may not encounter a conflict
Participant ID will now be issued
TU Delft
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D-5 Experiment Checklist

The consistency in the briefing is maintained by the briefing document and the briefing presentation. For maintaining the consistency in the computer lab, a tracking checklist was created that would dictate the flow of the experiment in the computer lab. This checklist is presented in the following page. The familiarization runs are represent by the suffix "F", the training scenarios by the suffix "T" and the measurement scenarios by the suffix "S". The order of measurement scenarios are filled in for each group as in the order shown in the scientific paper (Part I).

Lab Checklist

Check	Task
	Explain the Setup - Speed knob - Ref. Speed - Heading knob - Path to follow - ND Range Knob (TFC)
	F1 – Just fly and get a understand the response of your aircraft Change heading Change speed Change ND Range Take it your flight back to path Play: go out and come back onto the path. Maintain the same speed.
	F3H0 – Half run Half see Wait till Orange
	F4H5 – Half see Half run Wait till Orange
	F5H0 – Half run Half see Wait till Red
	F6H5 – Half see Half run Wait till Red
	F2AW – ALL watch and see - evolution and the protected zone - RPZ - Timing
	T1 – Pairwise conflicts
	Questionnaire – ID T1
	T2 – Pairwise conflicts w/ influence
	Questionnaire – ID T2
	T3 – Pairwise conflicts w/ influence (interchanged)
	Questionnaire – ID T3
	T4 – Pairwise conflicts w/ influence Scene 2
	Questionnaire – ID T4
	T5 – Pairwise conflicts w/ influence Scene 2 (interchanged)
	Break
	Questionnaire – ID T5
	Measurement Scenario 1
	Questionnaire – ID S1
	Measurement Scenario 2
	Questionnaire – ID S2
	Measurement Scenario 2
	Questionnaire – ID S3
	Questionnaire – Final
	Debrief and snacks

D-6 Questionnaire 1: Post-Run

The questionnaire that was asked for each participant at the end of each run within the experiment is attached in the following page.

Post-Run Questionnaire

"Multi-Actor Self-Separation in Complex Airspace Environments"

Instructions:
1. Please answer this questionnaire AFTER EACH RUN and click on Submit at the end of the form.
2. Once you click on Submit (on the last page), you won't be able to edit your responses.
3. If you have any doubts regarding the questionnaire, please raise your hand.. The experimenter will come to you to resolve your doubts.

* Required

1. **Participant ID (assigned at the beginning of the experiment):** *

2. **Run ID (provided at the end of each run):** *

3. **Did you encounter any conflict(s)?** *
Mark only one oval.
   - Yes *Skip to question 4.*
   - No *Skip to question 9.*

You indicated you encountered conflicts.

4. **What was the perceived level of difficulty of the very first conflict you encountered?** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Very Easy											Very Difficult

5. **Were you satisfied with how this conflict was resolved?** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Very dissatisfied											Very satisfied

6. **If you had a second chance at the same situation, would you change your approach?** *
Mark only one oval.
   - Yes *Skip to question 7.*
   - No *Skip to question 9.*

7. **Given that second chance, how would you change your approach from before?** *

8. **Why do you think this is a better approach than what you took?** *

9. **What was the level of mental effort you had to put in this run?** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Very little mental effort	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Mentally exhausted

End of the Questionnaire

10. **Do you want to submit your answers?** *
Mark only one oval.

◯ Yes, I want to submit my answers. *Stop filling out this form.*

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Google Forms

D-7 Questionnaire 2: Post-Experiment

The questionnaire that was asked for each participant at the end of the experiment is attached in the following page.

Post-Experiment Questionnaire

"Multi-Actor Self-Separation in Complex Airspace Environments"

Instructions:
1. Please answer this questionnaire AT THE END OF THE EXPERIMENT and click on Submit at the end of the form.
2. Once you click on Submit (on the last page), you won't be able to edit your responses.
3. If you have any doubts regarding the questionnaire, please raise your hand. The experimenter will come to you to resolve your doubts.

* Required

1. **Participant ID (assigned at the beginning of the experiment):** *

Please note: The following questionnaire is about the entire experiment and is not particular about any individual run.

2. **What was your most preferred strategy to resolve conflicts?** *
   Mark only one oval.
   - Sequential Resolution: Solve conflicts one by one as they arise
   - Global Resolution: Solve all conflicts at once with a single manaouver
   - A combination of both
   - Other:

3. **Why did you prefer this strategy?** *

4. **Comment on all of your used strategies and how it evolved to your most preferred strategy?** *

Background Information

5. **What is your sex?** *

Mark only one oval.

- ◯ Female
- ◯ Male
- ◯ Prefer not to say

6. **What is your age? (Enter 0 if you prefer not to say)** *

____

7. **Are you a gamer (PC, Xbox, PS, etc..)?** *

Mark only one oval.

- ◯ Yes, I play a lot
- ◯ Yes, occasional gamer
- ◯ Yes, but very rarely
- ◯ Not at all

8. **Do you have a pilot's license?** *

Mark only one oval.

- ◯ Yes
- ◯ No

9. **What is your specialization? (If not from MSc Aerospace, choose other and indicate your background, and specialization if applicable)** *

Mark only one oval.

- ◯ Aerodynamics and Wind Energy
- ◯ Control and Operations
- ◯ Spaceflight
- ◯ Aerospace Structures and Materials
- ◯ Flight Performance and Propulsion
- ◯ Other: ______________________________

10. **Were you familiar with the working of instruments of glass cockpit used in this experiment (Navigation Display, Mode Control Panel, EFIS Control Panel) before you read the briefing document?** *

Mark only one oval.

- ◯ Yes
- ◯ No

End of the Questionnaire

11. **Do you want to submit your answers?** *

Mark only one oval.

- ◯ Yes *Stop filling out this form.*

Appendix E

Data Imputation

As mentioned in the scientific paper (Part I), some highly unrealistic results from the experiment were imputed, for which the procedure is presented in this appendix.

A total four aircraft trajectories from the human-in-the-loop experiment showed unrealistic deviation from reality as shown in Figures E-1 (a), E-2 (a), E-3 (a) and E-4 (a). Though data represents situations without any intrusion, the trajectories flown by a single aircraft in each of these scenarios make no sense. As such, using this data would provide insight on unrealistic behavior. Since this is not desired, the data had to be removed or replaced. The loss of value of removing an entire group's data motivated exploring data imputation methods to salvage the realistic behavior as much as possible Gondara (2016); Ran, Tan, Feng, Liu, and Wang (2015); Tran, Zhang, and Andreae (2015). If the data imputation failed, only then would the scenarios of the entire group be discarded from further analyses.

The explored imputation methods suggested to interpolate the data based on the existing good data. However, considering this is a human-in-the-loop experiment, what this meant was to model human behaviour to interpolate and replace the bad data. It is well known that human behaviour modeling is still a hot topic of research. It would also be a big deviation from the present research. Since the procedures involved were not practical to be applied for the present situation, a simpler approach was used. The unrealistic aircraft trajectory of the given scenario was decided to be replaced with the one flown by another groups participant in a realistic manner for the same scenario and same aircraft. However, this needs to be analyzed for effects on other aircraft involved in the scenario. The replaced aircraft should blend in with the overall evolution of the particular scenario in time.

Fortunately, it was possible to replace all the unrealistic trajectories with realistic ones. This meant that there were four scenarios who had an aircraft trajectory exactly the same as in some other group for the same scenario. The effect of directly using the same aircraft trajectory in two different groups for the same scenario has very little effect because the performance of humans is analyzed per group and not by individual aircraft. Hence, the full correlation exists only in the aircraft trajectory level, but not in the group level or the scenario level.

Sections E-1, E-2, E-3 and E-4 present the individual cases of trajectory data imputation.

E-1 Trajectory 1

Figure E-1 (a) shows the scenario of the unrealistic aircraft trajectory. Figure E-1 (b) shows a scenario with a realistic trajectory for the same aircraft from a different group. Figure E-1 (c) shows the scenario after replacing the unrealistic trajectory from Figure E-1 (b) with the realistic trajectory from that of Figure E-1 (b).

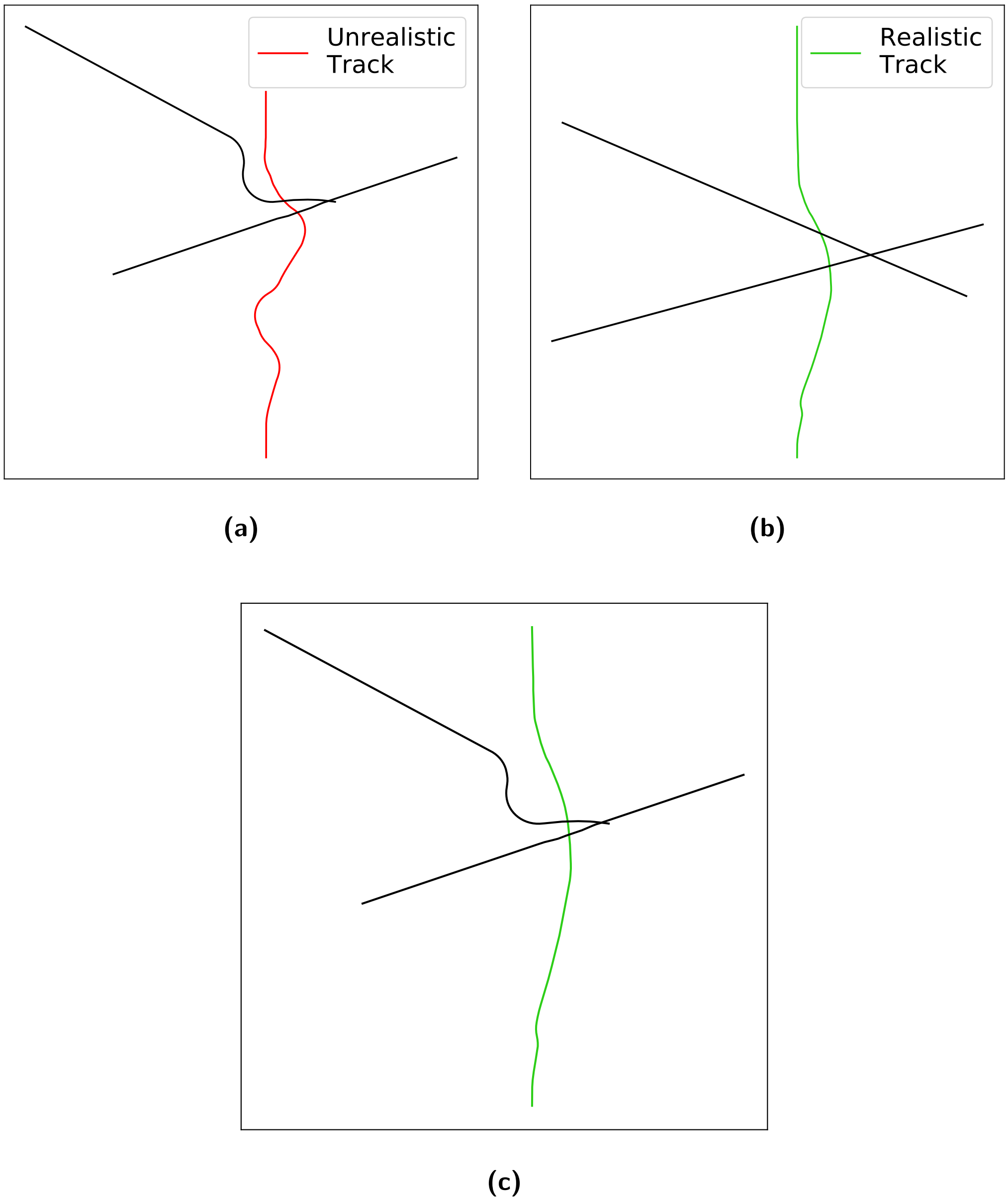


Figure E-1: Scenario with unrealistic aircraft trajectory: case (1)

E-2 Trajectory 2

Figure E-2 (a) shows the scenario of the unrealistic aircraft trajectory. Figure E-2 (b) shows a scenario with a realistic trajectory for the same aircraft from a different group. Figure E-2 (c) shows the scenario after replacing the unrealistic trajectory from Figure E-2 (b) with the realistic trajectory from that of Figure E-2 (b).

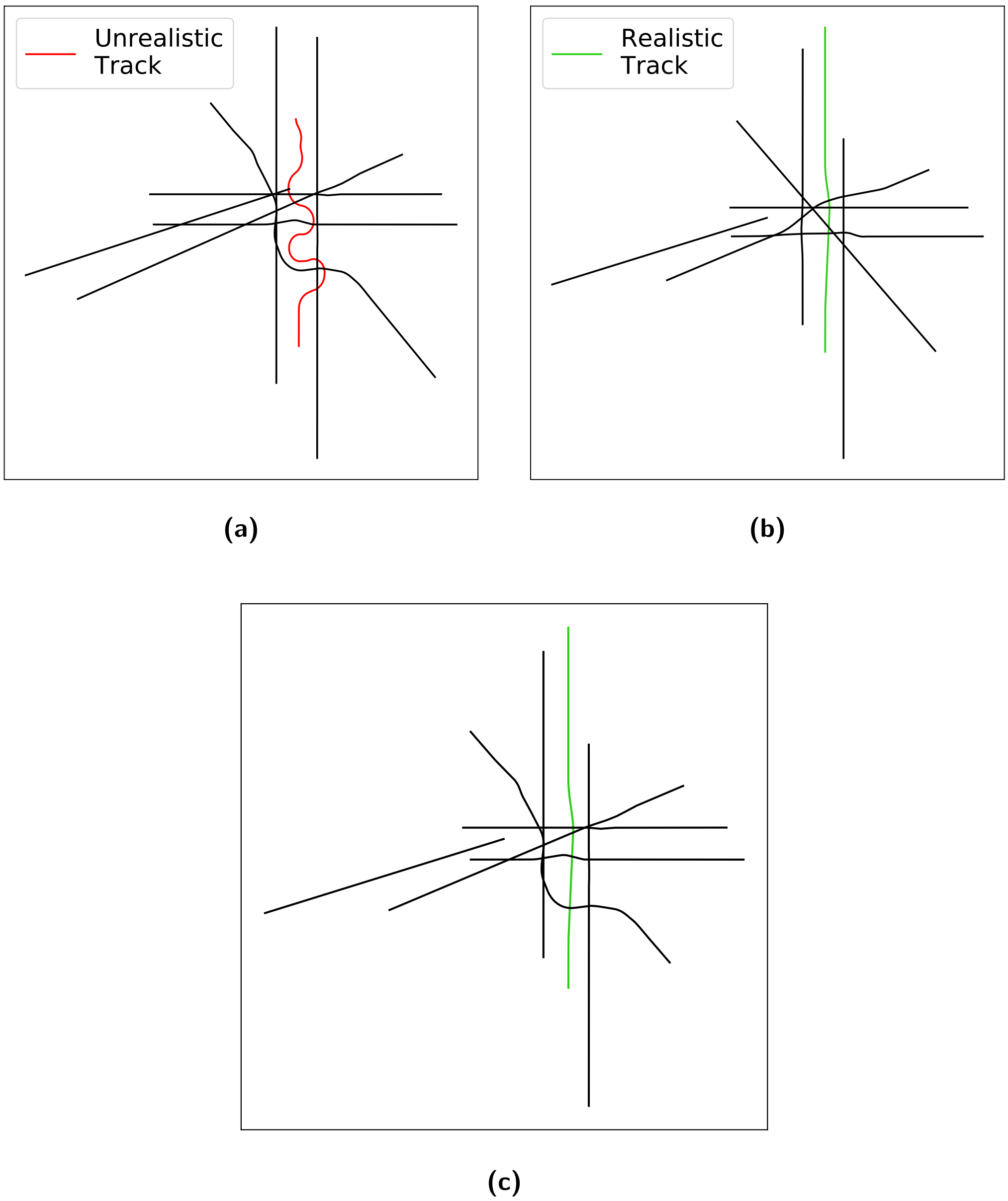
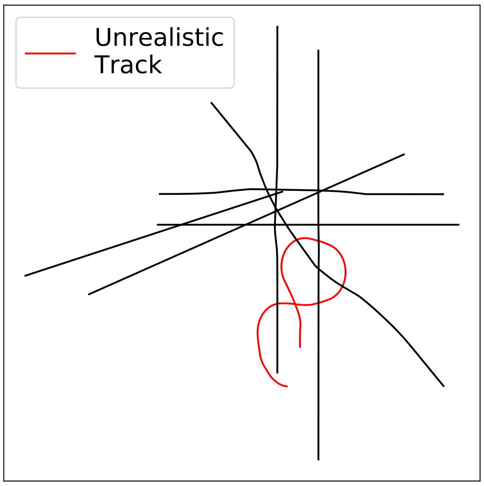


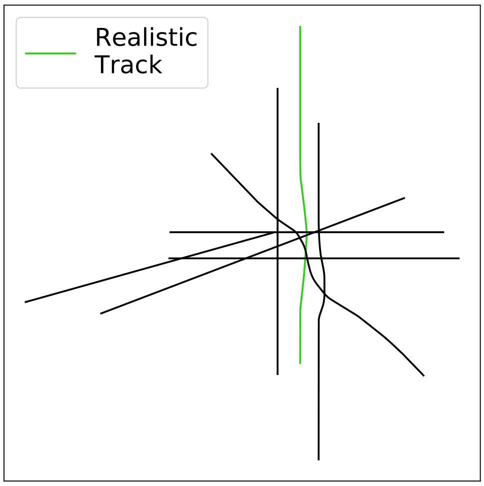
Figure E-2: Scenario with unrealistic aircraft trajectory: case (2)

E-3 Trajectory 3

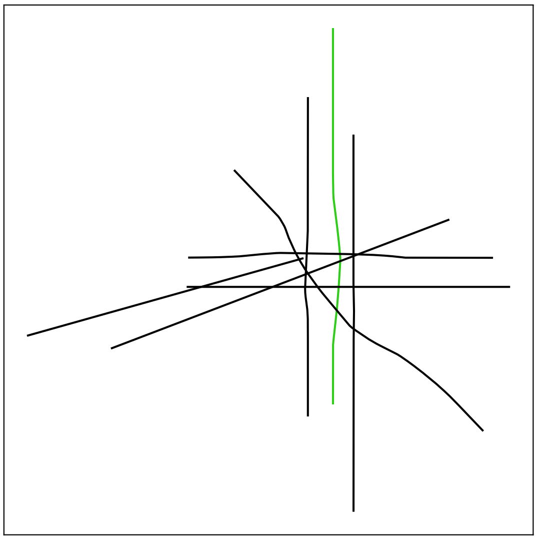
Figure E-3 (a) shows the scenario of the unrealistic aircraft trajectory. Figure E-3 (b) shows a scenario with a realistic trajectory for the same aircraft from a different group. Figure E-3 (c) shows the scenario after replacing the unrealistic trajectory from Figure E-3 (b) with the realistic trajectory from that of Figure E-3 (b).



(a)



(b)

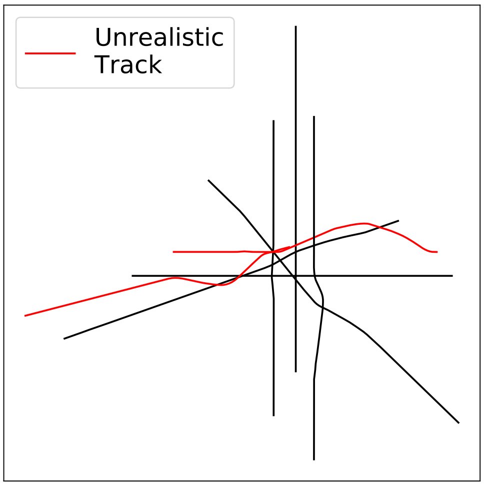


(c)

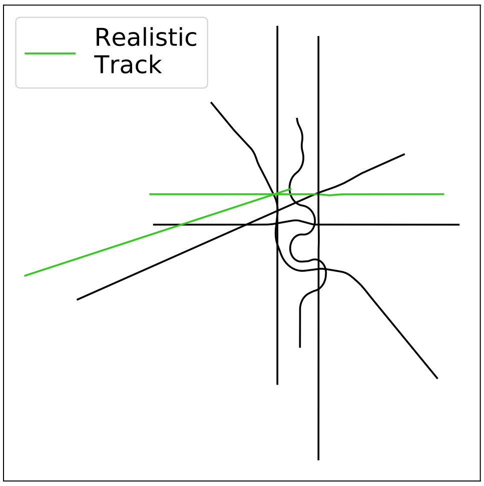
Figure E-3: Scenario with unrealistic aircraft trajectory: case (3)

E-4 Trajectory 4

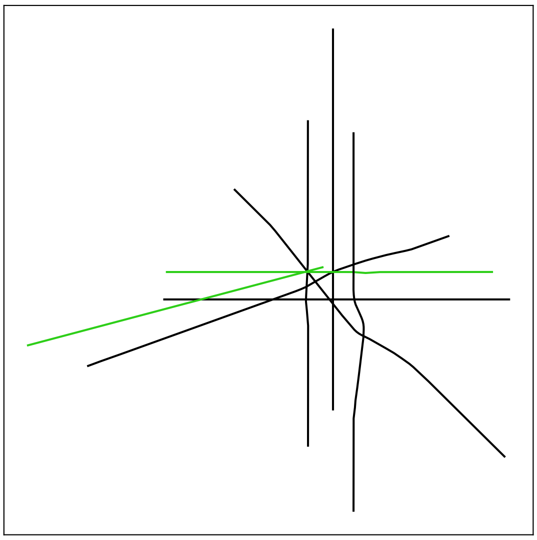
Figure E-4 (a) shows the scenario of the unrealistic aircraft trajectory. Figure E-4 (b) shows a scenario with a realistic trajectory for the same aircraft from a different group. Figure E-4 (c) shows the scenario after replacing the unrealistic trajectory from Figure E-4 (b) with the realistic trajectory from that of Figure E-4 (b).



(a)



(b)



(c)

Figure E-4: Scenario with unrealistic aircraft trajectory: case (4)

Appendix F

Additional Results

In this appendix, additional results are presented that are part of the thesis, but not mentioned in the scientific paper in Part I.

F-1 Participant Statistics

A total of 41 subjects participated in the experiment. The participants were specifically chosen from field of aerospace engineering at least at the master level of studies. Of the 41 participants, 38 were master students and 3 were PhD candidates. The age of the participants was normally distributed from 21 to 29 years ($\mu = 24.24$ years, $\sigma = 1.68$ years). Less that six participants were regular gamers and remaining being occasional or rare gamers.

F-2 Traffic Complexities Calculated from the SSD

As mentioned is Part I, the traffic complexity as seen by individual aircraft can be captured by the SSD display, referred to as the SSD complexity. The SSD complexity is calculated as the percentage area of the SSD that occupied by the FBZ.

The SSD complexities were calculated and averaged for each group for each group. The following figures show the variation of the SSD complexity over time for the average and maximum SSD complexities per scenario.

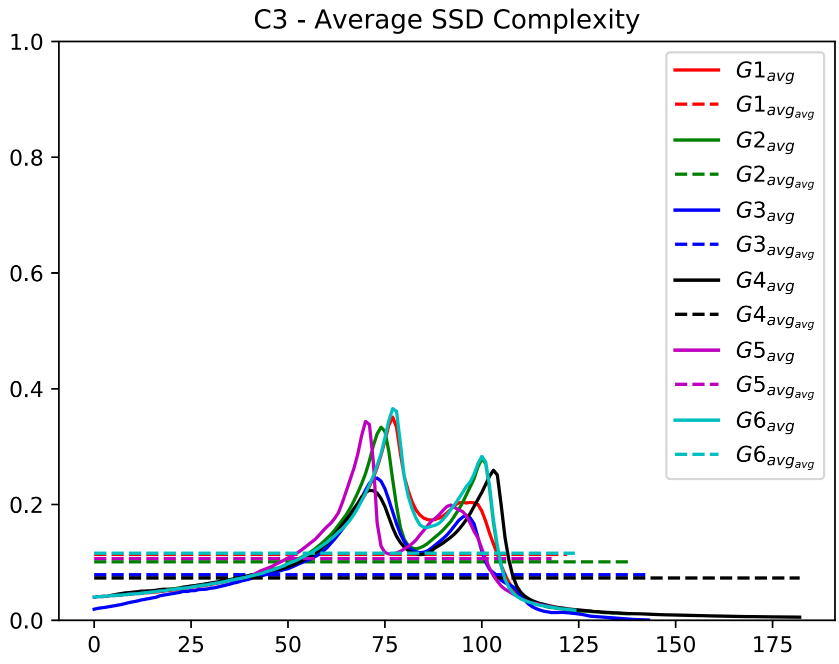


Figure F-1: Average SSD Complexity for C_3

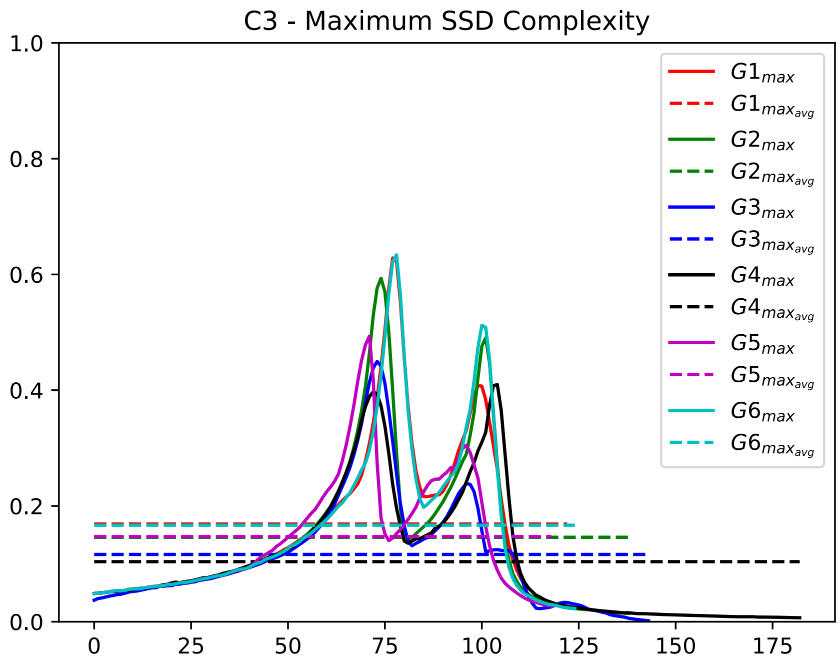


Figure F-2: Maximum SSD Complexity for C_3

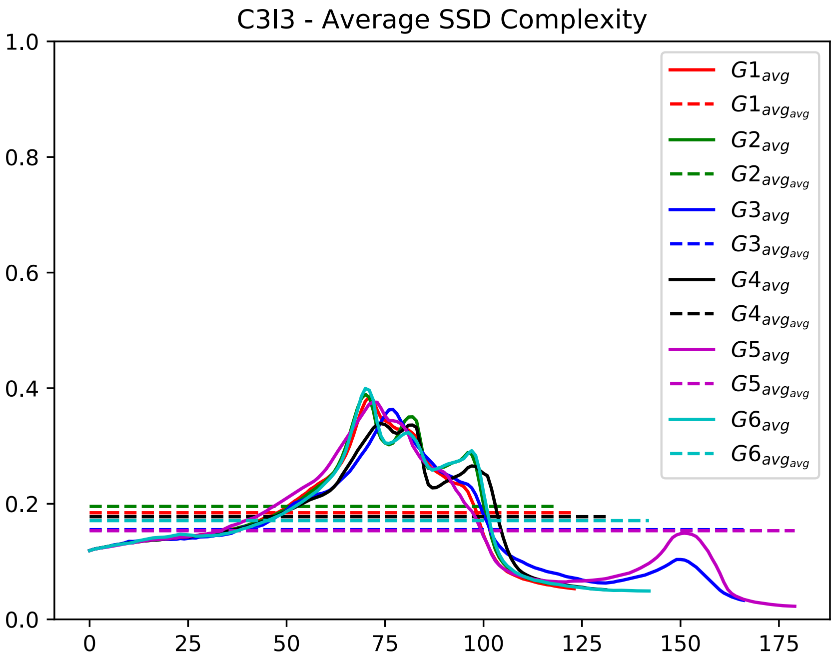


Figure F-3: Average SSD Complexity for C_3I_3

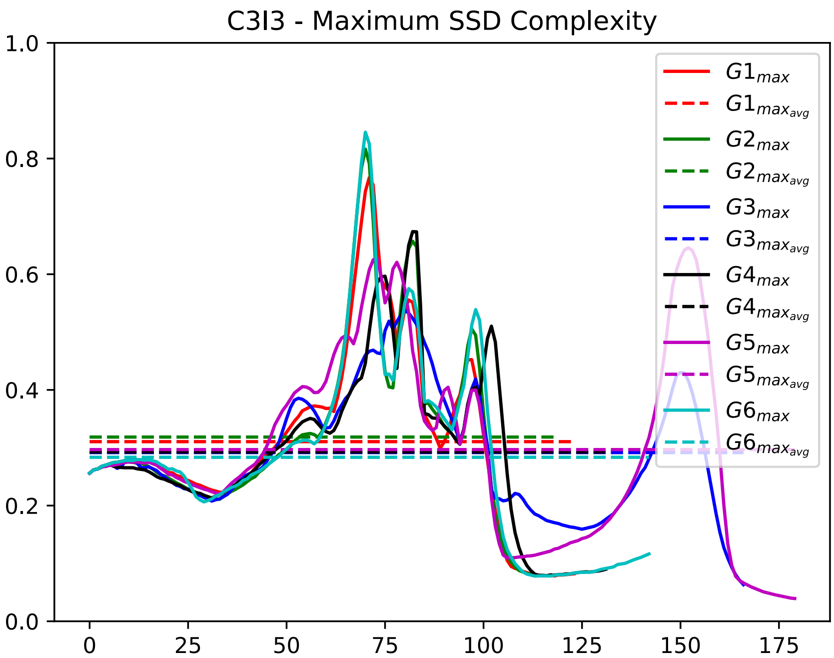


Figure F-4: Maximum SSD Complexity for C_3I_3

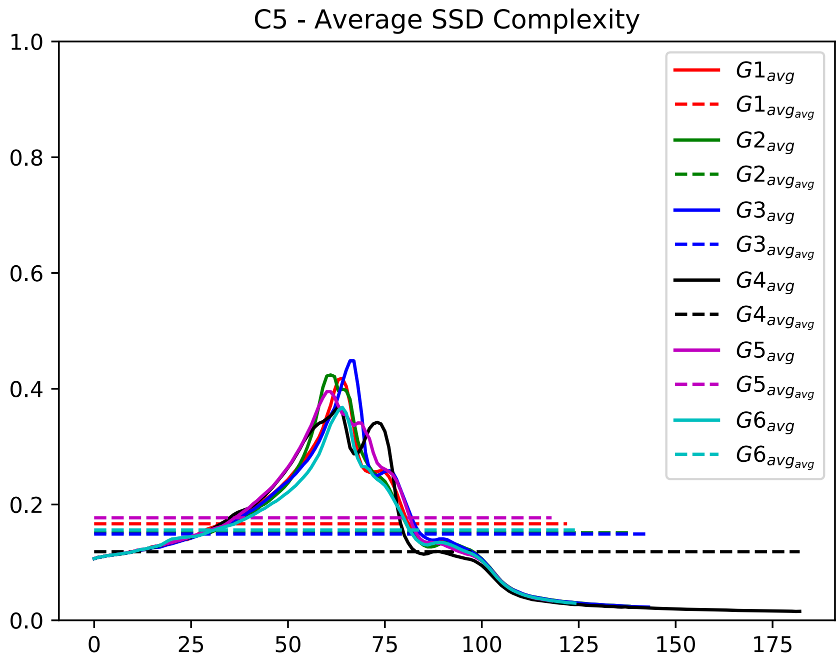


Figure F-5: Average SSD Complexity for C_5

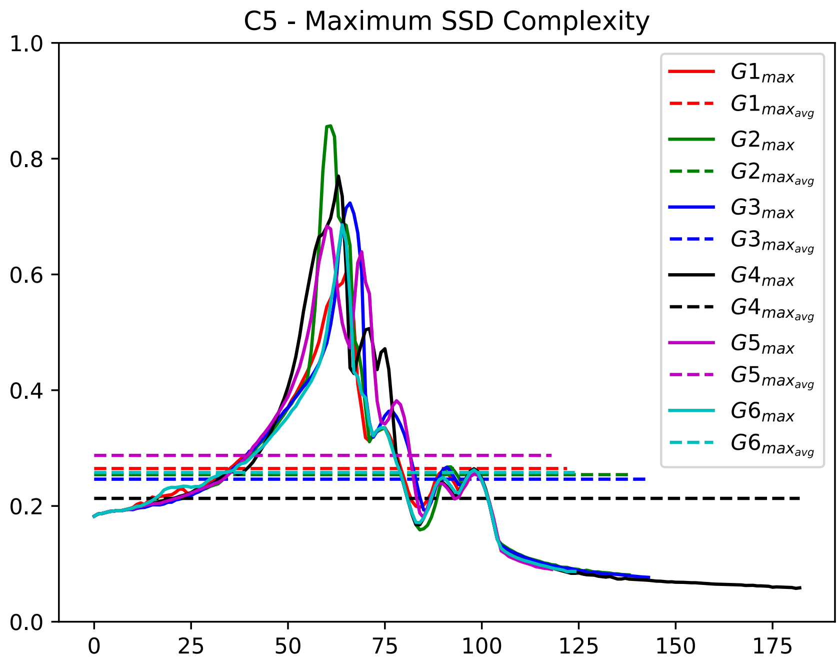


Figure F-6: Maximum SSD Complexity for C_5

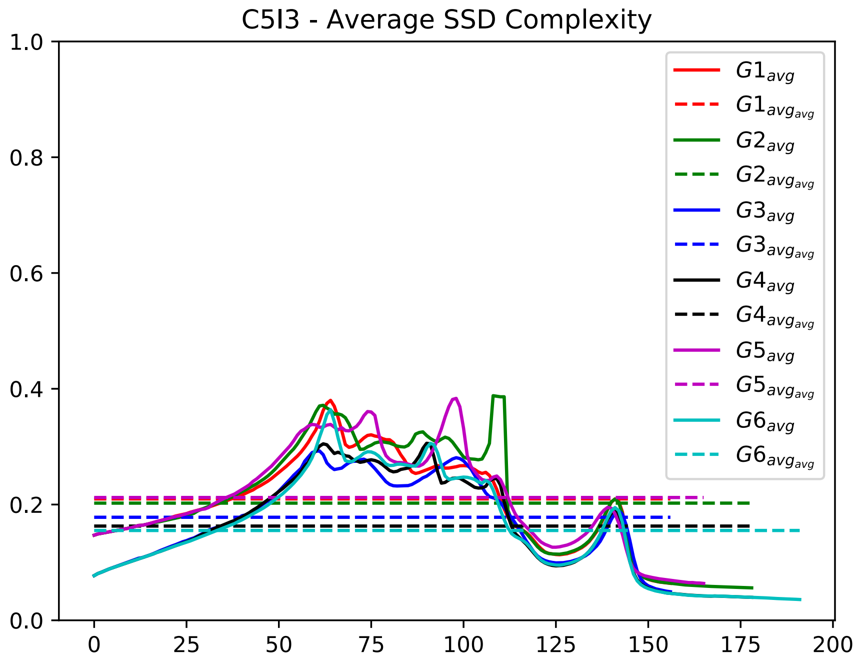


Figure F-7: Average SSD Complexity for C_5I_3

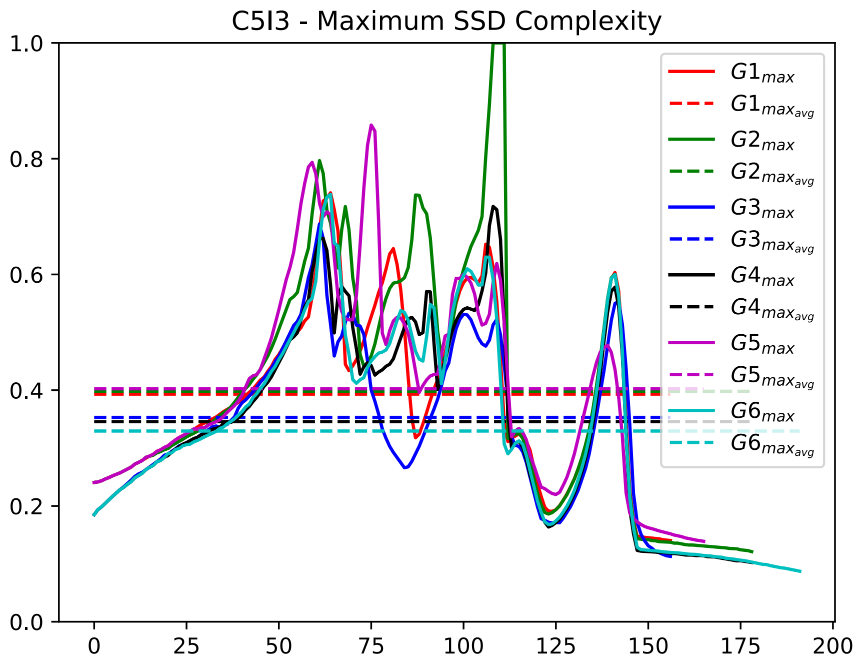


Figure F-8: Maximum SSD Complexity for C_5I_3

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