Cooperative 4D-Trajectory Management for Future Air Traffic Control

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Challenge the future

Cooperative 4D-Trajectory Management for Future Air Traffic Control

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by

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to obtain the degree of Master of Science
at the Delft University of Technology

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled "**Cooperative 4D-Trajectory Management for Future Air Traffic Control**" by **Radesh Nagaraj** in partial fulfillment of the requirements for the degree of **Master of Science**

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Preface

Before the reader lies the result of months of hard work on my Master Thesis Project titled "Cooperative 4D-Trajectory Management for Future Air Traffic Control", in order to graduate at the department of Control & Simulation at the Faculty of Aerospace Engineering at Delft University of Technology. This report contains a scientific paper which presents the results in a compact and a concise manner, a thesis book of appendices in which I describe a more in-depth information, clarification for further reading. I started this project at the start of spring 2016 and have since worked on it with great motivation and enthusiasm.

I could not have finished this thesis without the help of my support cast. First of all, I would like to thank my daily supervisor dr.ir. Clark Borst, who constantly motivated and inspired me to work hard. His valuable feedback was crucial which kept me striving for quality while working on this thesis project. He has been my advisor for the masters course as well and was never short of words, always inspiring me with his amazing sense of humor. He has been the best guide and words cannot describe how grateful I am for his support, which has been pivotal to the successful completion of my thesis and masters program. Secondly, I would like to thank ir. Rolf Klomp for all the insightful discussions we had regarding the Travel Space tool and also for his recommendations for designing the scenarios for the experiment. Furthermore, I would like to thank dr.ir Rene van Paassen for his razor-sharp and accurate questions which was helpful for me to better evaluate and understand the concepts more throughly and clearly. Also prof.dr.ir Max Mulder for his constant motivation which always pushed me to achieve excellence by working hard. My gratitude goes out to all the thirteen participants who spared three hours of their valuable time in order to take part in my experiment. The effort and time invested by the participants have been crucial in the successful completion of this thesis project.

Next, I would like to thank my current flat mates Ashwathi and Sumana, who took care of me these past couple of months by making sure I ate food at the correct time, so that I was rejuvenated to continue working. Thanks to Arjun for all his insights on Latex. Much thanks to Shravan for his patience in explaining me the concepts of automating a script on MATLAB. Also much thanks to Ashwathi who constantly motivated me during some of my most testing days. Thanks to Kashmira for taking the extra time to peer review the report and providing me with your crisp and concise feedback. Thanks to Suhas for guiding me whenever I was stuck with a problem. Last but not least, I would like to thank my parents and my sister, who have always been supportive of my studies, without which this masters course would not have been a reality. All in all, this two years at TU Delft has been a profound and diverse experience which I will never forget, teaching me some important lessons on the way. This thesis does not only conclude my graduation project, but also marks the end of my studies at TU Delft. I look back with amazing and happy memories.

Radesh Nagaraj
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Delft, December 22, 2016

ACRONYMS

ATM	Air Traffic Management
ATCo	Air Traffic Controller
SESAR	Single European Sky ATM Research
NextGen	Next Generation Air Transportation System
ADS-B	Automatic dependent surveillance - Broadcast
IATA	International Air Transport Association
TBO	Trajectory Based Operations
EID	Ecological Interface Design
CD&R	conflict detection and resolution
TSR	Travel Space Representation
SSD	Solution Space Diagram
FMS	Flight Management System
HMI	Human Machine Interface
HITL	Human-in-the-Loop Experiment
CTA	Controlled Time-of-Arrivals
ASAS	Airborne Separation Assistance Systems
SWIM	System-Wide Information Management
RTA	Required Time of Arrival
AOC	Airline Operations Center
MCP	Monotonic Concession Protocol
ATSP	Air Traffic Service Providers
DST	Decision Support Tools
ETMS	Enhanced Traffic Management System
PVD	Plan View Display
DD	Dynamic Density
CO-ATM	Co-Operative Air Traffic Management
NGATS	Next Generation Air Transportation System
SACR	Single-Aircraft Conflict Resolution
MACR	Multi-Aircraft Conflict Resolution

LIST OF FIGURES

List of Tables

CONTENTS

PART- I

MASTER OF SCIENCE THESIS PAPER

Cooperative 4D-Trajectory Management for Future Air Traffic Control

R. Nagaraj, C. Borst, M. M. van Paassen, M. Mulder

Abstract—**Future Air Traffic Management (ATM) is expected to shift towards four dimensional trajectory management, requiring new decision support tools for air traffic controllers (ATCo) to adhere to stringent time and flight performance constraints. In previous research a new prototype has been developed which used Travel Space Representation (TSR) principle that allowed only the trajectory manipulation of single aircraft. In this research, the potential benefits of multi-aircraft trajectory manipulation has been investigated for flight efficiency and preservation of airspace robustness. Instead of controlling only one aircraft, controllers can manipulate and revise trajectories of multiple aircraft. A human-in-the-loop experiment has been designed with varying conflict angles and aircraft pairs. The controllers managed to re-route all the aircraft safely, without any loss of separation. They preferred to use multi-aircraft clearances for lower conflict angles, which resulted in better robustness when compared to single-aircraft commands. So even though the multi-aircraft trajectory manipulation resulted in better robustness it did not always result in less added track miles. The use of multi-aircraft clearances depended on the preference of the participant and traffic structure. Current implementation of multi-aircraft clearances involves re-routing all the aircraft through one way-point (merge point). In complex traffic situation this might result in increased workload for the controller. Therefore instead of creating one way-point, creating more than one merge-point will result in more separation for the aircraft and reduce the monitoring time for the controller.**

Index Terms—**Single-Aircraft Conflict Resolution, Multi-Aircraft Conflict Resolution, control action, robustness**

I. Introduction

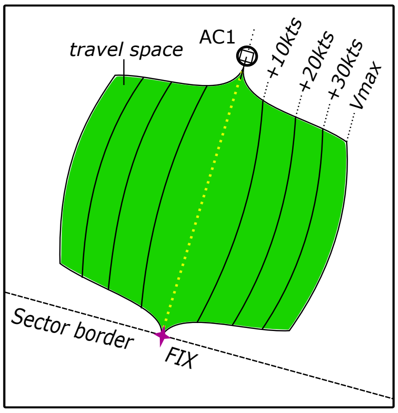
TRAJECTORY Based Operations (TBO) is a concept proposed by Next Generation Air Transportation System (NextGen) and Single European Sky ATM Research (SESAR) [2] [3]. The concept here is to introduce a new control variable - time, which allows the Air Traffic Controllers (ATCo) to shift control strategies from current tactical decisions toward longer-term strategic decisions. TBO with 4DT makes the job of a controller more complex. The goal of NextGEN and SESAR is to make the airspace more efficient and robust to withstand uncertainties on a longer time scale.

SESAR and NextGen have a clear framework regarding the future of ATM, but does not have a well-defined regulation for the design of the automation tools (i.e., interface etc.), which will be used to assist the ATCo. Currently, research on several prototype interfaces is underway. One such example is an interface designed by Klomp et al., which uses the Travel Space Representation (TSR) principle to manipulate the 4D trajectories of the aircraft [1] [7]–[10]. Travel Space is a concept where a visual representation of safe field of travel (safe control actions) is provided, which allows a controller to safely revise the 4D trajectories of individual aircraft [7]. When the trajectory of an aircraft is manipulated using the TSR, the travel space ensures that the aircraft strictly adheres to time constraints set within an airspace sector, aircraft performance (i.e., the speed envelope and turn characteristics) and overall airspace safety (separation assurance) [7] [11].

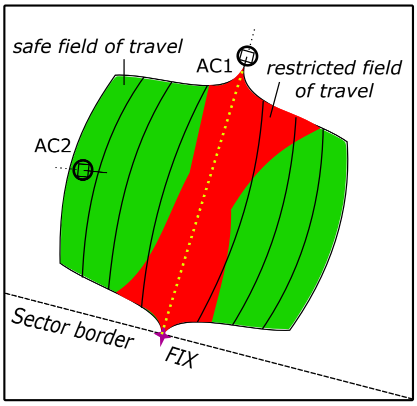
Klomp et al., evaluated the effects of robustness for varying level of expertise of controllers [9]. As defined by Klomp et al., "Robustness is a quantitative measure of trajectory flexibility which has been defined as the ability of an aircraft to adhere to planned trajectory and imposed constraints, irrespective of probabilistic random state deviations from the trajectory" [7]. A human-in-the-loop experiment was conducted, wherein the controller could make use of only Single-Aircraft Conflict Resolution (SACR) to resolve the conflicts. The participants level of expertise varied from novice to expert. Results showed that the TSR interface aided the participants to preserve the airspace robustness. Added track miles were more pronounced for the expert group, mainly because they preferred strategies which made the aircraft fly with larger separation buffers, instead of flying close to the constraint boundaries which would result in reduced track miles [9]. The future ATM system focus is on cooperative ATM, wherein the responsibility of conflict resolution is shared between the aircraft and the ground [15] [16].

Cooperative 4D trajectory sequencing is one of the possible solutions which gives strategic control to ATCo. The idea here is to have multiple aircraft fairly sharing the cost (e.g., added track miles) of a re-route or evasive maneuver [17]. In order to tackle the above stated problem, this research mainly concentrates in filling the gap between current technology (manipulation of one aircraft) and future cooperative technology by answering this main research question: *Can a cooperative 4D trajectory interface with multiple-aircraft conflict resolution (MACR) be beneficial in terms of preserving airspace robustness compared to single-aircraft conflict resolution (SACR), without sacrificing safety, efficiency and not increase controller workload?* A human-in-the-loop experiment has been designed wherein the controller can make use of both SACR and MACR control option to resolve the conflicts. Results are compared in terms of efficiency based on the chosen control option (SACR or MACR) to resolve the conflict.

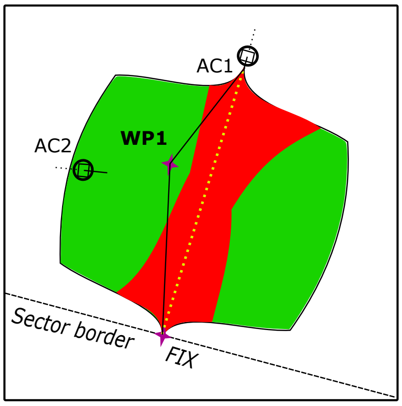
The paper is structured as follows. In Section II the description



(a) TSR for one aircraft in the airspace



(b) TSR for AC1 (conflict)



(c) Intermediate way-point is placed

Fig. 1: TSR for Single-aircraft conflict resolution [1].

of SACR and MACR are explained. Following this, the calculation of robustness for both the control option is described in Section III. In Section IV the experimental design for the human-in-the-loop is described. Results from this experiment will be discussed in Section V. Finally the recommendations and conclusions are presented in Section VI and Section VII.

II. Single vs Multi-Aircraft Conflict Resolution

In this section the difference between single-aircraft conflict resolution (SACR) and multi-aircraft conflict resolution (MACR) is explained. A brief explanation of a batch study which was conducted to investigate the change in robustness for both control actions (i.e., SACR and MACR). Later the results from this batch study are presented.

A. Single-Aircraft Conflict Resolution (SACR)

In order to illustrate the working of Travel Space Representation (TSR) for SACR and to see how it supports the controller in trajectory revisions, TSR in its simple form having single-aircraft conflict resolution capability is shown in Figure 1 [1]. The aircraft shown in the sector will have to adhere to strict time constraints within the airspace sector boundary. TSR for an aircraft (AC1) is shown in Figure 1(a). Depending on the aircraft turn characteristics the shape of the TSR changes close to the aircraft current position and the metering fix. The overall shape of the TSR is bounded by the maximum achievable speed within the aircraft performance envelope [1].

In Figure 1(b), another aircraft (AC2) enters the airspace. TSR for AC1 changes from being all green to a red band (no-go) area in the center. This is due to the fact that AC1 is in a potential conflict with AC2. If both the aircraft continue flying in this trajectory, a collision is imminent. In Figure 1(c) an intermediate way-point is placed on the green area of TSR of AC1 (go area). The conflict will not be resolved if the intermediate way-point is placed within the red-band (no-go) area. The operator can accept this new way-point and the trajectory is automatically changed and the airspace sector will become conflict free (Figure 1(c)). The amount of added track miles depends on the placing of the new intermediate way-point. Placing this way-point on the extreme boundary of the TSR will result in the aircraft flying more distance and also increase the speed at which it has to fly (to meet the exit time constraint).

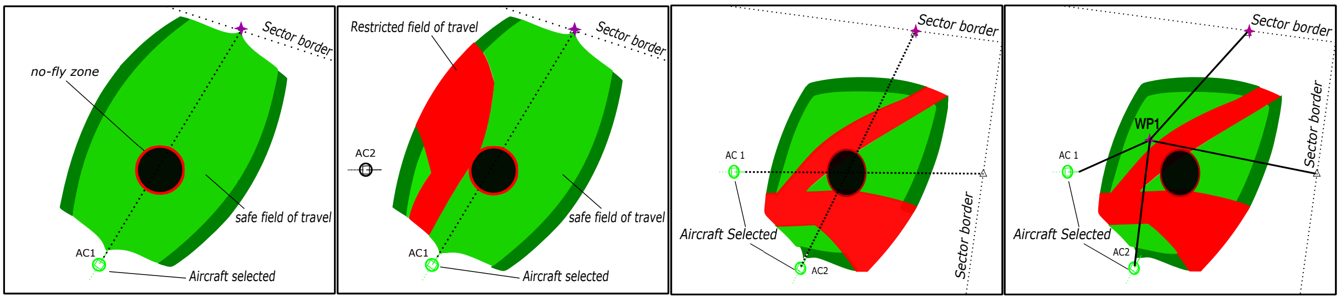
B. Multi-Aircraft Conflict Resolution (MACR)

The TSR for MACR works in a similar way as SACR. Here instead of clicking on any one aircraft, the controller will have to click on multiple aircraft. It can be observed from Figure 2 the change in the TSR when multiple aircraft are selected to resolve the conflict. A no-fly zone (forbidden zone) is present in the shown example. Figure 2(a) shows the TSR for AC1 which is conflict free. In Figure 2(b) AC2 enters the airspace and the TSR for AC1 changes to a set of feasible (green area) and infeasible regions (red area). When only one aircraft i.e., AC1 is selected, the TSR for AC1 is shown in Figure 2(b).

In order to see the MACR TSR the controller has to select both AC1 and AC2 (Figure 2(c)). The TSR shown in Figure 2(c) is the overlap of the individual TSR for AC1 and AC2, and the resultant TSR is the set of feasible and infeasible regions for both AC1 and AC2. In order to resolve the conflict, the controller will have to place a new intermediate way-point in the feasible region (green area). In Figure 2(d) a new way-point "WP1" is placed in the feasible (green area) region. After selecting this way-point, the trajectories of both AC1 and AC2 changes and will converge towards this point (merge point) but at different times thereby resolving the conflict.

C. Batch Study

Klomp et al., investigated whether the TSR can be used to maintain airspace robustness without compromising efficiency (added track miles in *nm*) for a two aircraft crossing scenario under varying geometry [7]. In this experiment a single-aircraft



(a) TSR for one aircraft in the airspace (b) TSR when AC1 (in conflict with AC2) is selected (c) TSR when both AC1 and AC2 is selected (d) Intermediate way-point (WP1) is placed

Fig. 2: TSR for Multi-aircraft conflict resolution.

conflict resolution was provided to resolve the conflict. To ensure a fair calculation of robustness for all the experiment conditions, the time taken for closest point of approach (CPA) of flights before and after conflict was set to 10 minutes [7]. In this batch experiment, no intermediate way-points were created (edge of infeasible region), instead the time of entry for the second aircraft was varied such that at CPA of one aircraft either passes in-front or behind the other aircraft.

Using the results from this experiment as a baseline, a preliminary analysis was conducted to investigate and compare the change in robustness for varying conflict angles and maneuvers for both single-aircraft and multi-aircraft conflict resolution. The two maneuvers were: 1) one aircraft maneuvered behind the other and 2) one aircraft maneuvered in front of the other. In Figure 3, θ is the conflict angle and it was varied from 30° to 150° and only two aircraft were considered for this batch study which were in conflict with each other.

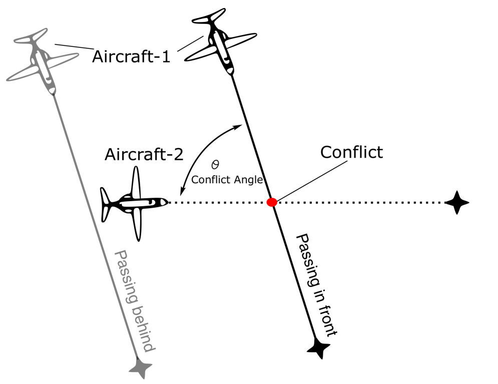
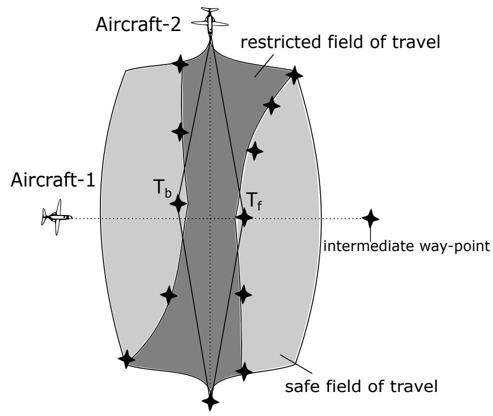
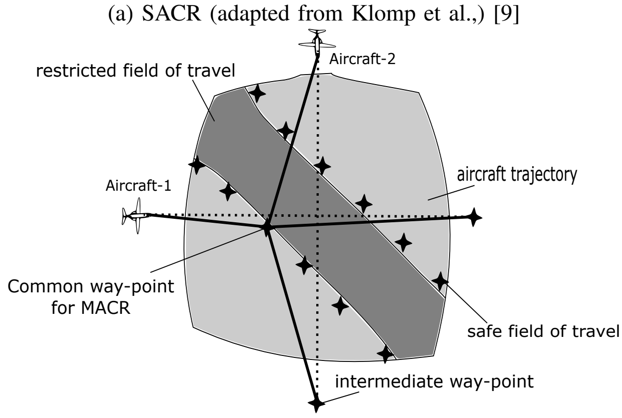


Fig. 3: Definition of conflict angle and maneuvers for the preliminary analysis.

For this batch study, instead of changing the time of entry of the second aircraft, the new intermediate way-point was placed on the edge of the separation standard minimum (infeasible region) first by using SACR and then by MACR to resolve the conflict (see Figure 4). T_b is the trajectory when Aircraft-2 passes behind Aircraft-1 and T_f is the trajectory when it passes in front of Aircraft-1. The change in robustness and the number of added track miles was calculated. The intermediate way-points were placed randomly along the stretch of the feasible region (green area) from one end to another (entry to exit point of aircraft). Depending on the size of the TSR each conflict angle scenario was further divided into individual way-point scenario (different way-points along the edge of separation minimum). Only one intermediate way-point was placed at a time in each simulation run. Robustness and number of added track miles was calculated for every individual way-point location. This can be visualized from the TSR representation for a 90° conflict angle shown in Figure 4.



(a) SACR (adapted from Klomp et al.,) [9]



(b) MACR

Fig. 4: TSR for 90° conflict angle with intermediate way-points marked for both SACR and MACR.

The metric which was used to calculate the robustness for SACR and MACR are explained here.

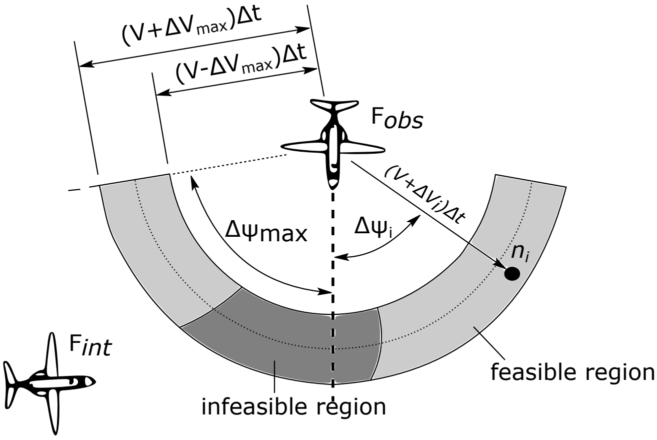


Fig. 5: Geometry and the Point-based robustness at a discrete point n_i (adapted from Klomp et al. [9]).

Consider two aircraft, observer (F_{obs}) and intruder (F_{int}) as shown in Figure 5, which are in conflict. It should be noted that the movement of aircraft is restricted to only 2D + time. Consider aircraft F_{obs} at a given time (t), and at each point in time its predicted state will be (t,x,y,V,ψ). Next states at which robustness will be calculated is t + Δt. Let ΔV be the velocity with which aircraft is traveling and ΔV_{max} be the maximum velocity. Similarly $\Delta\psi_{max}$ be maximum heading change the aircraft is capable of making. A probabilistic disturbance model is used to model the speed and heading disturbances [9].

For a given look ahead time, an aircraft will have speed offset of ($-\Delta V_{max} \leq \Delta V \leq \Delta V_{max}$) and heading offsets of ($-\Delta\psi_{max} \leq \Delta\psi \leq \Delta\psi_{max}$). Where ΔV_{max} is the maximum velocity and $\Delta\psi_{max}$ is the maximum heading angle offset. Consider a point n_i with heading angle offset $\Delta\psi_i$. Robustness is calculated on every point till n_i for a time interval Δt on the trajectory. This results in a "disc shaped area" within which the aircraft is predicted to be at an interval (t+Δt). After discretizing all the data points, two sets of results will be available in the TSR namely 1) set of feasible trajectories and 2) set of infeasible trajectories.

These two segments are shown in Figure 5, where the dark gray area represents the infeasible region due to the predicted loss of separation with the other aircraft F_{int}. Placing a new intermediate way-point in this region will not eliminate the conflict. The light gray area is the feasible region. Speed characteristics are also included in the design of the interface. Thereby, when a new intermediate way-point is placed away from the original trajectory, the aircraft will need to fly faster (within the maximum speed characteristics) in order to meet the time constraints set at the exit way-point. With this speed characteristics, again the entire process of calculating the robustness on every point on this new trajectory is reiterated to check for any loss of separation with the other aircraft. Therefore by definition, robustness at a considered point on the trajectory can be defined by the following equation (adapted from [9]).,

$$RBT(t) = \sum_{i=1}^{f} P_i(t) = \frac{N_f(t,x,y)}{N(t,x,y)}, \tag{1}$$

where,

$RBT(t)$	= Robustness
$P_i(t)$	= Probability
$N_f(t,x,y)$	= Number of feasible trajectories at a point and
$N(t,x,y)$	= Total number of feasible trajectories (without disturbance)

D. Results

The value of robustness was calculated for each of the intermediate simulation run for all the conflict angles. The airspace is said to be more robust when its value is close to 1. Therefore the least value or minimum robustness (RBT_{min}) for every simulation run was calculated and these values were plotted as shown in Figure 7. In order to keep the results comparable to the bath study conducted by Klomp et al., the following variables were kept constant for the calculation of robustness value [7]:

- Look forward time: the aircraft scan for potential conflicts from current time (t) to a set time (Δt) of 120 seconds
- Maximum heading difference (ψ_{max}) is set to 80°
- The maximum speed disturbance is set to 20 kts IAS (ΔV_{max})
- Heading angle was discretized with 5 degrees
- Speed range in interval of 10 kts IAS

Figure 6 shows the result of average added track miles [*nm*] for all the scenarios. It can be observed that, only for 30° conflict angle the value of average added track miles is lower when MACR is used. For all other conflict angles the added track miles is more when MACR is used over SACR.

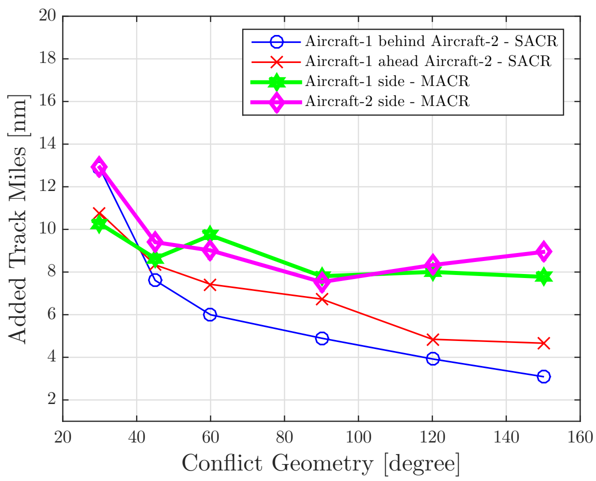
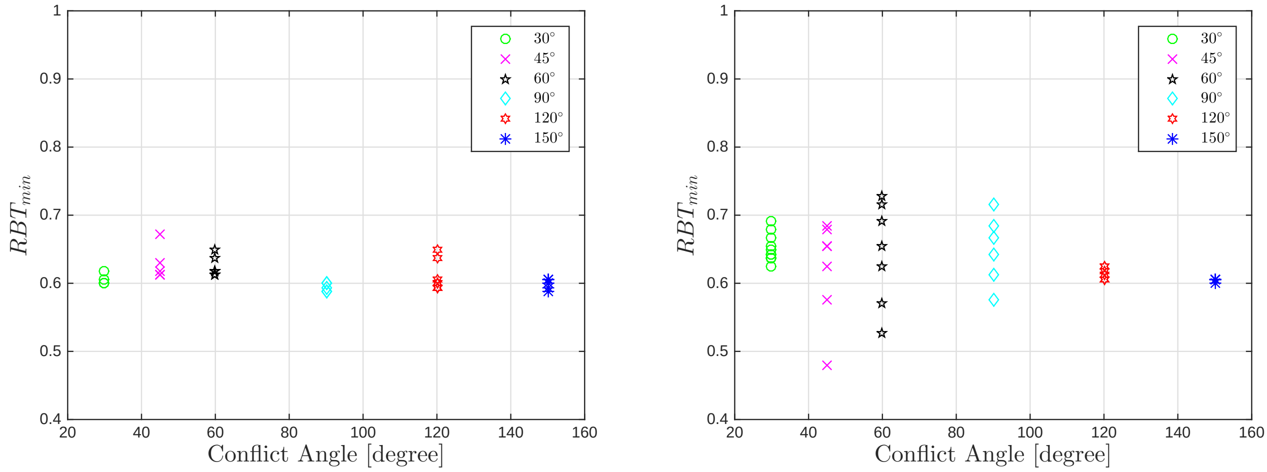


Fig. 6: Average track miles for all the conflict angles.

Results showed that the robustness value is better for lower conflict angles (30° - 90°) when MACR is used and for the



(a) RBT$_{min}$ - Aircraft-1 behind Aircraft-2 scenario (SACR)

(b) RBT$_{min}$ - Aircraft-1 behind Aircraft-2 scenario (MACR)

Fig. 7: RBT$_{min}$ for all the scenarios.

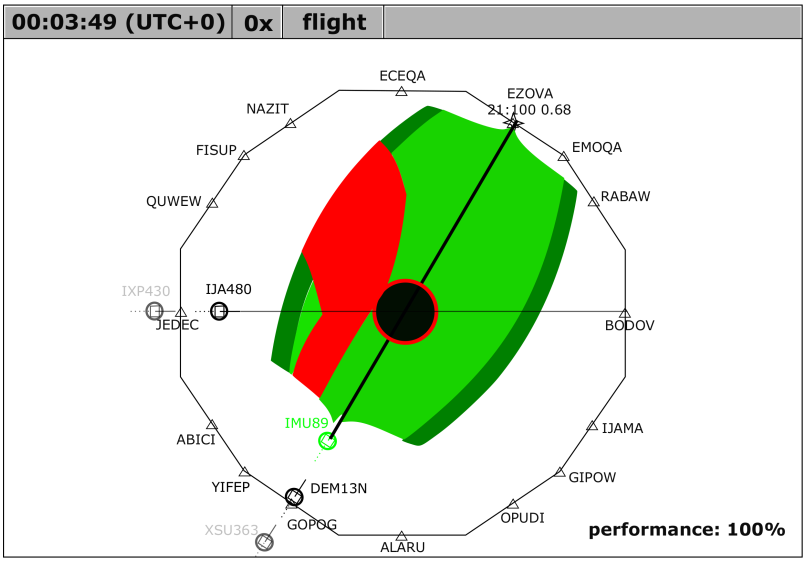


Fig. 8: Screenshot of the simulation interface.

maneuver when one aircraft flies behind the other aircraft. For higher conflict angles the robustness value was similar for both SACR and MACR. It can be observed from Figure 7(b) that some values of robustness were worse when MACR was used over SACR. After further investigation, it was found that the robustness value depends on the position of the new intermediate way-point while resolving the conflict.

III. Experiment Design

An experiment has been designed and conducted to evaluate which control action (i.e., SACR or MACR) is preferred by controllers as a function of conflict angles and conflict pairs. Additionally, the experiment also measured the safety (robustness) and efficiency (added track miles (*nm*)) based on the given control action.

A. Apparatus

The experiment was conducted in the Air Traffic Management Laboratory (ATMLab) in the faculty of Aerospace Engineering, TU Delft. An LCD monitor was used as the main display interface in this research, from which the participants could see the 4D interface with the TSR representation (see Figure 8). The scope of the task was limited to only pure lateral changes to resolve conflicts with no longitudinal (i.e., altitude) and speed changes. The placement of intermediate way-point location would change both the heading and speed of the aircraft. When a conflict is detected, participants could click on the aircraft pair involved in the conflict using a mouse. After clicking, the available safe area of travel (i.e., TSR) was shown. The participant could place a new intermediate way-point by clicking anywhere on the "go-area" and press enter

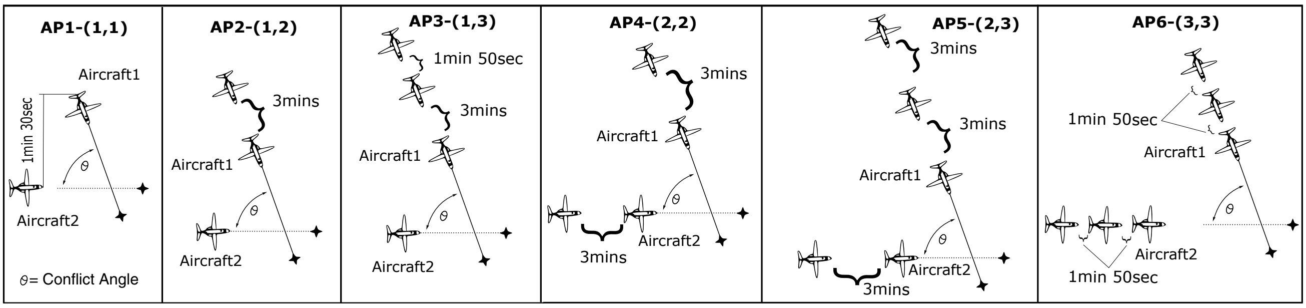


Fig. 9: Scenario design of all six aircraft pairs for 30° conflict angle.

to select, which will execute the trajectory revision thereby eliminating the conflict. It was assumed that an Automatic dependent surveillance - Broadcast (ADS-B) data link was used for communication between controller and aircraft and all heading change commands were automatically executed.

B. Independent Measures

In this experiment two within-subjects independent variables were defined:

- Conflict angle: Preliminary analysis showed that MACR is beneficial at lower conflict angles (Section II-C). Aircraft pairs with different conflict angles was used in every scenario. Conflict angles of 30°, 60° and 120° are used in this experiment.
- Aircraft Pairs: At a time aircraft could enter the airspace in only two streams as shown in Figure 8. In total six aircraft pairs were considered in this experiment as shown in Table I. In order to show the benefits of MACR in specific traffic situations when compared to SACR, aircraft pair was considered as an independent variable. Figure 9 shows how the six aircraft pairs were designed in a scenario, θ was varied between 30°, 60° and 120°.

TABLE I: Aircraft Pair

	Aircraft Pair (AP)
AP-1	(1,1)
AP-2	(1,2)
AP-3	(1,3)
AP-4	(2,2)
AP-5	(2,3)
AP-6	(3,3)

C. Control Variables

The control variables considered for this experiment were as follows:

1) Flight Level: All the aircraft in the airspace flew in an en-route airspace at flight level 290.
2) Aircraft Performance: Only one type of aircraft was used in all the experimental runs i.e., Airbus A320.
3) Sector Elements: The size and shape of the airspace sector was fixed spanning 140*nm* from end to end. Each airspace had a "no-go" area or a forbidden zone designed at the center of the actual airspace. The shape of the forbidden zone was a circle with a radius of 10*nm* (Figure 8). The number of way-points in the airspace was fixed, but the names of the way-points were changed for each experiment run, in order to eliminate confounds due to scenario recognition.
4) Human-Machine Interface: The interface from which Conflict Detection and Resolution (CD&R) can be visualized was kept constant throughout the experiment. The input devices through which visualization of the TSR could be activated and providing conflict resolution was also kept constant (mouse and keyboard).

D. Participants & Instructions

Thirteen participants (2 females and 11 males with an average age of 30 years) took part in the experiment. It was made sure that the participants had an experience or knowledge of ATC to aid error free experimentation. Among the thirteen participants, four were staff members (ATC researchers) and nine were students.

Before the start of the measurement runs all the participants were given a pre-experiment briefing, which comprised of all the instructions required for the experiment. Their main control tasks for this experiment were 1) to maintain a separation of five nautical miles (5*nm*-minimum separation standards) between aircraft at all times and 2) to reroute all the aircraft whose trajectory intersected the forbidden zone around it, making sure they minimize the path deviation and the number of control actions.

In addition to this, the general working of the interface was also explained. It was made clear that the total time for the completion of a scenario would differ for each scenario, and the experimenter would instruct them regarding which scenario to start after the end of the current scenario. The order of the experiment conditions and other specific information about the experiment was withheld from the participants. The participants were instructed that they could use either SACR or MACR clearances for conflict resolution. And the TSR only considered the conflict zones of those aircraft which were inside the airspace sector. As such, participants were instructed to plan ahead before implementing their specific control actions.

E. Experiment Procedure

The participant was asked to read the experiment briefing before the start of the measurement runs. In total there were three main phases in the experiment 1) pre-experiment briefing, 2) training phase and 3) a measurement phase. The participants were requested to think-out loud about their strategies in the measurement runs. This strategy was recorded using a video camera, which also recorded the LCD screen. After the measurement runs, there was a de-briefing session for five minutes, which concentrated mainly on the aspects and personal opinions of the traffic situation in the experiment. After the completion of the de-brief session, the participant was requested to fill out an online questionnaire form.

The training phase comprised of eight training runs, which allowed the participants to get used to the working of the simulator and familiarize themselves about the interaction with the input devices and the interface. The traffic complexity in the training runs increased steadily so that the participants were not overwhelmed with the number of aircraft in the scenario. As explained in the above sections, this experiment had an extra type of control action available in order to resolve the conflicts i.e., multi-aircraft conflict resolution (MACR). Therefore, each training run was specially designed, such that the benefits and disadvantages of both the control actions (SACR and MACR) could be readily noticed. And the participants were given the choice to decide which option to choose in order to resolve the conflicts. The last two training runs used the same airspace design as the actual measurement runs. Here, the participants were advised to think-out loud their strategies (about the resolution to be executed) before the aircraft entered the airspace, so that they were already familiar in terms of the talking points for the measurement runs.

The measurement run consisted of six scenarios. A latin square distribution of the experiment scenario was used to randomize experiment conditions to eliminate any control bias due to scenario recognition and carry-over effects in the measurement runs. Sufficient breaks were given to the participants, after the training runs and also between the measurement runs to avoid fatigue.

F. Scenarios

The main task of the participants in this experiment was to manage traffic in an hypothetical en-route sector. The independent variables considered were conflict angles and aircraft pairs. Therefore the entire experiment was divided into six different experiment conditions. The airspace shape and size remained the same in all the six scenarios. Each scenario was designed with a forbidden zone ("no-go area") at the center with a radius of 10*nm* (see Figure 8). There were fifteen way-points through which the aircraft could enter and exit the airspace sector. The names of all the way-points and aircraft ID's were varied in each of the scenario in order to prevent any confounds due the scenario recognition. The simulation time for each scenario was about 40-60 minutes. The simulation was made to run at four times (4x) the normal speed, that allowed more measurement runs in less time. Thus each scenario lasted about 10-15 minutes in real time. Each scenario was further rotated in order to eliminate control-bias due to scenario recognition. The order of rotation is shown in Table II. Therefore in total there were 12 scenarios. In order to balance the independent measures, six measurement runs were conducted.

TABLE II: Experiment Scenarios rotation

Condition	Rotated	Condition
Scenario1	90°	Scenario2
Scenario3	180°	Scenario4
Scenario5	180°	Scenario6
Scenario7	180°	Scenario8
Scenario9	90°	Scenario10
Scenario11	180°	Scenario12

The aircraft could enter the airspace sector through any one of the way-points. At a time there were only two streams of aircraft with varying conflict angles entering the airspace. In one scenario all three conflict angles (i.e., 30°, 60° and 120°) with one of the six aircraft pairs was designed (see Figure 9). Therefore, in total there were three conflict angles and three aircraft pairs in one scenario. Eg., For aircraft pair (2,2): There will be two aircraft in both the streams (total of 4 aircraft) which will be self separated in time. Henceforth, AP means aircraft pair and AP-(i,j) where i is the number of aircraft in one stream and k is the number of aircraft in the other stream.

Both aircraft pairs and conflict angles were randomized in every scenario. Hence, over the six scenarios each conflict angle would have been paired with all the six aircraft pairs (AP), thus balancing the two independent variables used in the experiment. Each aircraft entering the airspace sector was initially given a straight (4D) trajectory heading towards the other way-point. All the initial trajectories of the aircraft intersected the forbidden zone. The participants had to re-route the aircraft trajectory such that they do not intersect the forbidden zone. In order to limit the scope of the results, only lateral trajectory revisions were possible and controllers could revise the trajectories only if the aircraft were already inside the airspace. Nonetheless, participants could see the inbound approaching aircraft as a gray symbol, such that they were aware that more aircraft were coming in, and could already start thinking about their strategy to resolve them.

The aircraft trajectories which are designed in this experiment were conflict free. However, the participants could create more conflicts based on the provided control actions. Each aircraft was separated by time (see Figure 9). This time based separation ensured that each aircraft would fly behind the other aircraft. The example shown in Figure 9 are for conflict angles 30° and 60°. For 120° conflict angle the separation was further increased to 5 *mins* for aircraft pairs (1,2), (2,2) and (2,3). The time based separation for aircraft pair (3,3) remained the same at 1 *min* 50 *seconds* for all the three conflict angles. And also between Aircraft-1 and Aircraft-2 the time based separation was 1 *min* 30 *seconds* for 30° and

60° conflict angle, whereas for 120° conflict angle it was 2 *mins* 30 *seconds*. The participants were given the choice of both SACR and MACR to resolve the conflicts.

G. Dependent Measures

The following dependent variables were used in this experiment:

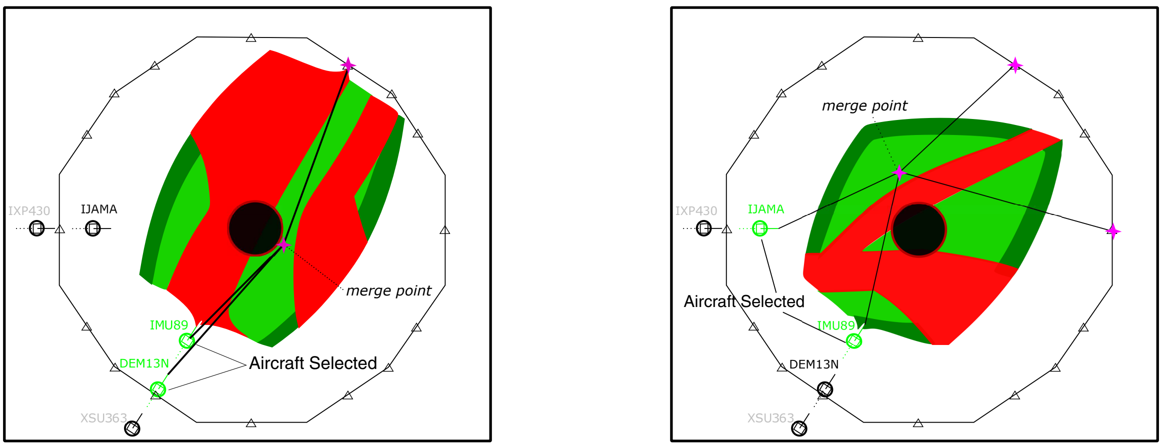
- Safety
  - Airspace robustness with respect to control action was measured (Eq. 1)
  - Forbidden zone (no-fly zone) intrusions
  - loss of separation (protected zone intrusions)
- Efficiency
  - The added track miles flown (with respect to both the control actions), ideally the original path flown by aircraft was a straight line from entry to exit.
  - Type of Control Action: The preferred control action and the number of times each control action used was measured. The two control actions which were made available for this experiment are:
    1) Single-Aircraft Conflict Resolution (SACR): As the name suggests, the participant can re-route or manipulate the trajectory of only one aircraft at a time.
    2) Multi-Aircraft Conflict Resolution (MACR): Using this control action the participant could re-route or manipulate the trajectories of more than one aircraft (multiple aircraft) at a time. MACR command is further divided into two types:
       * Same Stream: the conflict is resolved by selecting more than one aircraft which are flying in the same stream (Figure 10(a)).
       * Inter-Stream: the conflict is resolved by selecting more than one aircraft which are flying in two different streams (Figure 10(b)).
- Workload: Instantaneous self assessment (ISA), an automatic workload bar would be displayed once in every seven minutes in simulation time on the left edge of the LCD monitor. The controllers could click on the workload rating bar which was refined with a rating of 1-100 to measure even a minute change in workload as perceived by the participant.

H. Hypotheses

- **H1: Airspace robustness will be better when MACR is used for lower conflict angles.** It was hypothesized that when comparing SACR with MACR, the latter will result in better preservation of robustness for lower conflict angles (less than 90°). For higher conflict angles it is expected that there will not be any significant difference in robustness value irrespective of the type of resolution used.

- **H2: MACR will be preferred for those aircraft which are close to each other within the same stream, but controllers will prefer SACR if the separation between the aircraft is more.** Irrespective of the conflict angle, for aircraft pairs (1,3) and (3,3), wherein the aircraft are close to each other in the same stream, controllers will opt for MACR over SACR (see Figure 9). This is because with one control action, three aircraft can be re-routed simultaneously instead of re-routing them individually. Aircraft pairs such as (2,2) and (2,3) where the aircraft from one stream will cross each other (aircraft) in the other stream, the participants will prefer to use SACR over MACR.

- **H3: Added track miles will be relatively more for lower conflict angles with SACR than MACR.** Whereas for higher conflict angles, irrespective of conflict angle and aircraft paring the extra added track miles will be similar when both the control actions are used.



(a) Same Stream (b) Inter-Stream

Fig. 10: Definition of Same and Inter-Stream MACR command.

IV. Results

A. Data Analysis

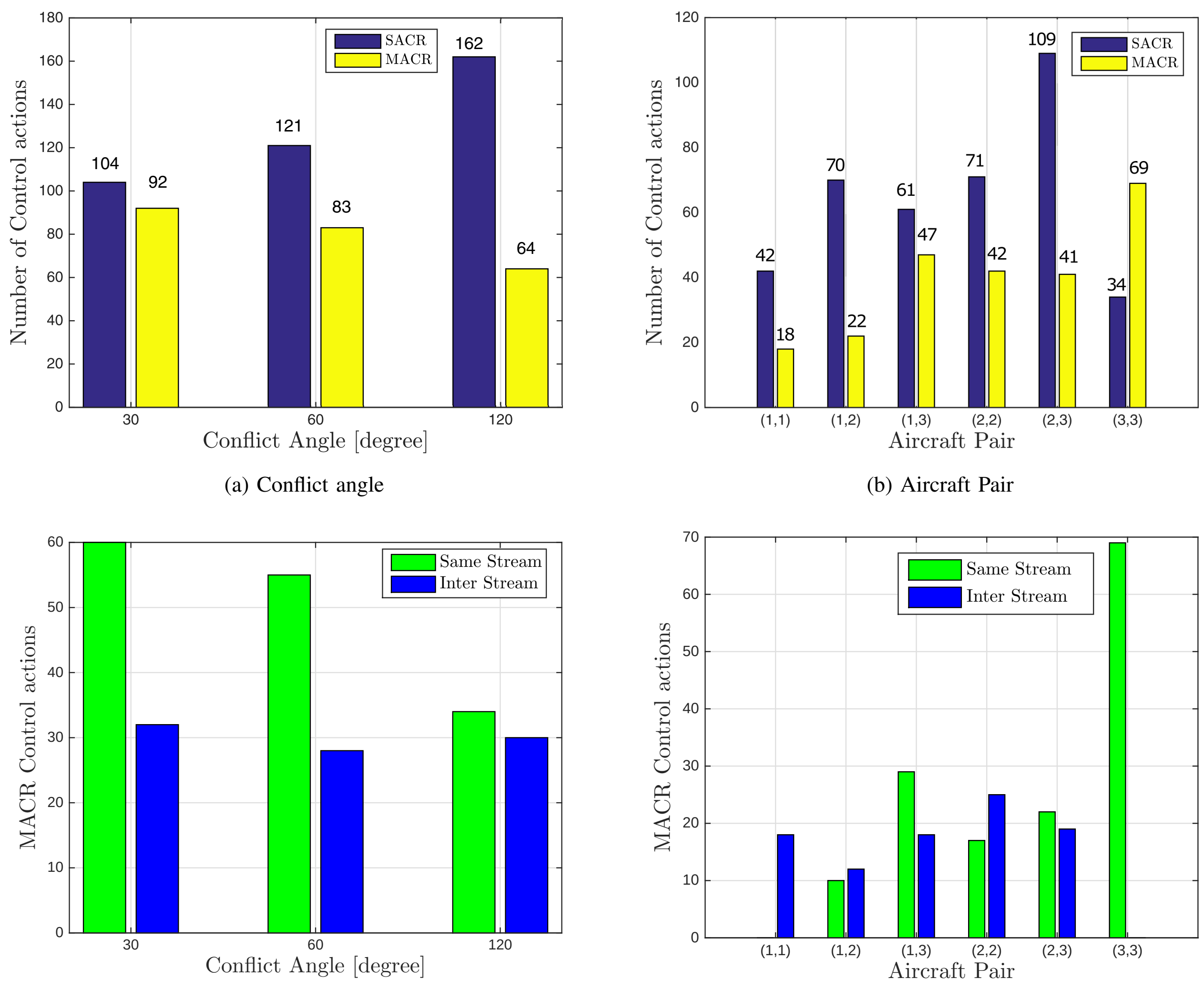
For the post-hoc calculation of robustness, the same variables as considered for the batch study (see Section II-D) are considered. Statistical tests such as Friedman test and Wilcoxon Signed-rank test have been performed to test the within-subject effects. The significance value (α) has been fixed at 0.05. Pairwise comparison has been conducted to investigate the effects of aircraft pairs (i.e., (1,1), (1,2), (1,3), (2,2), (2,3) and (3,3)) and conflict angles (i.e., 30°, 60° and 120°).

Also, robustness for all the experimental scenario was calculated 1) without the influence of forbidden zone (no-go area) and 2) with the influence of forbidden zone (no-go area). The results for the second case are shown in the Appendix G of this report. In the entire experiment there were no forbidden zone and protected zone (loss of separation) intrusions. First let us have a look at the results of number of control actions according to the conflict angle.

B. Type of Control Action

1) Conflict Angles: In the entire experimental runs of thirteen participants, a total of 626 control actions were implemented, out of which 387 were SACR commands and 239 were MACR commands. This was further divided based on the conflict angles, as shown in Figure 11(a). It can be seen from Figure 11(a), in all the three different conflict angle cases the number of SACR commands are more than MACR commands.

Out of the 239 MACR commands, some number of MACR commands were used for multi/inter-stream (aircraft from two different streams). Figure 11(c) shows the bar-graph for the number of MACR commands with respect to same or multi/inter stream aircraft. It can be noticed that MACR command was used for aircraft within same stream more often than



(a) Conflict angle

(b) Aircraft Pair

(c) Conflict angle-

(d) Aircraft Pair

Fig. 11: Number and type of control actions categorized by conflict angles and aircraft pairs.

TABLE III: Friedman Test Statistics^{a} - Control Actions

	Aircraft Pair					
	AP1-(1,1)	**AP2-(1,2)**	AP3-(1,3)	AP4-(2,2)	**AP5-(2,3)**	**AP6-(3,3)**
Total N	13	**13**	13	13	**13**	**13**
χ^2	7.369	**23.727**	1.114	5.334	**17.238**	**32.462**
df	5	**5**	5	5	**5**	**5**
p-value	0.195	**0**	0.953	0.376	**0.004**	**0**

aircraft from inter-streams. Only for 30° conflict angle case the inter MACR command was used more often as compared to inter MACR command for the other two conflict angles. This was because as the conflict angle increases, resolving the conflict using MACR command would have resulted in a head-on stream which the controllers wanted to avoid.

2) Aircraft Pairs (AP): Figure 11(b) shows the plot for SACR and MACR commands used by all the participants with respect to the aircraft pairs. It can be seen from the results that, when the separation distances between the aircraft were higher (i.e., for aircraft pairs (2,2) and (2,3)), SACR command was used more extensively over MACR commands. Whereas for aircraft which were in close proximity in the same stream, such as for aircraft pairs (1,3) and (3,3) MACR command was preferred over SACR. This trend is more pronounced for the aircraft pair (3,3). Here, MACR commands were used in more cases than SACR commands which thus proves hypothesis H2.

Figure 11(d) shows the bar-plot of number of MACR commands with respect to inter or same streams. It can be noticed from Figure 11(d) that for aircraft pair (3,3), all the MACR commands were infact executed for aircraft flying in the same stream. Also for the aircraft pair (1,3) majority of the MACR commands were for same stream aircraft. This is because, in both the cases the aircraft were flying closely one behind the other. For aircraft pair (1,1) since both the aircraft were flying from two different streams all the MACR commands were indeed inter stream MACR commands. For aircraft pair (2,2) inter stream MACR were much higher in number than same stream MACR commands. Since the separation between the aircraft were more, participants opted to use inter MACR commands to resolve the conflict.

A non-parametric test was conducted on the data for the number of control actions. A Friedman test was conducted for each of the six aircraft pairs. The results from the tests are described in Table III. It can be observed from the Friedman test statistics table (Table III) that the p-value is less than 0.05 for conditions AP2, AP5 and AP6 and the number of control actions are significantly different in these conditions. Hence, it can be concluded that there is a significant difference in the number of control actions for AP2, AP5 and AP6.

A post-hoc test, Wilcoxon signed-rank test was also carried out. A comparison was made between two sets of experimental conditions (i.e., SACR and MACR). Since the number of pair-wise comparison is 1 (i.e., k = 1), the adjusted α value (Bonferroni correction of the significance threshold) remain as 0.05. The result from the Wilcoxon Signed Ranks test is shown in Table IV. For 120° conflict angle in AP2-(1,2), a p-value of 0.034 was found to be significant than the other two conflict angles. Here, the number of SACR commands were more significant than number of MACR commands. For the AP5-(2,3) with conflict angle 120°, a & p-value of 0.05 was found to be significant than the other two conflict angles. Similar to AP2, even in this case the number of SACR commands were more significant than number of MACR commands for AP5 (2,3). For AP6-(3,3) with conflict angles 30° and 120° were found to be significant than 60° with a p-value of 0.02 and 0.033 respectively. For both 30° and 120° conflict angles the number of MACR commands were more significant than SACR commands.

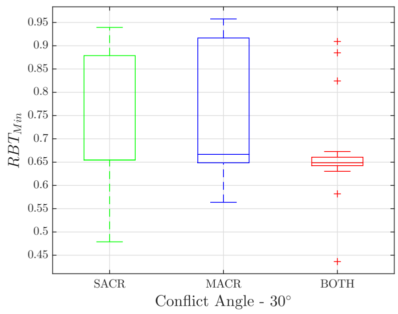
TABLE IV: Wilcoxon Signed Ranks test for number of control actions

AP2-(1,2)	Z	p-value
30°-SACR/MACR	0	1
60°-SACR/MACR	0	1
120°-SACR/MACR	**-2.115**	**0.034**
AP5-(2,3)	Z	p-value
30°-SACR/MACR	-1.761	0.078
60°-SACR/MACR	-0.778	0.436
120°-SACR/MACR	**-2.795**	**0.005**
AP6-(3,3)	Z	p-value
30°-SACR/MACR	**-2.324**	**0.02**
60°-SACR/MACR	-1.343	0.179
120°-SACR/MACR	**-2.138**	**0.033**

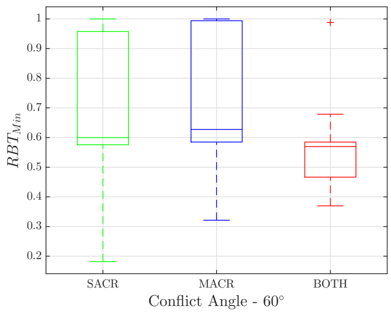
C. Safety - Robustness (Airspace Flexibility)

1) Conflict Angles: Ideally the airspace will be at its best robustness (i.e., 1) value when there are no aircraft in the airspace or if the aircraft are flying straight without any restrictions. But the robustness (RBT_{min}) decreases when aircraft are close to each other or when they fly in close proximity to the forbidden zone. Each command (i.e., SACR or MACR) affects the airspace robustness. While analyzing the robustness data, the least robustness (RBT_{min}) for each control action and the time of execution of each command was noted. Using this the least RBT_{min} value at that time interval was calculated. While computing the RBT_{min} value, the interaction of the aircraft with the forbidden zone (no-go area) was not considered, as the change in RBT_{min} can be noticed with fine detail. Results considering the influence of the forbidden zone (no-go area) are shown in the appendix section in this report.

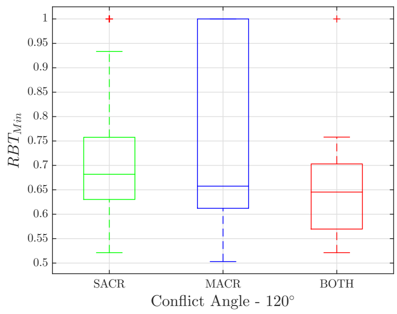
Figure 12 shows the box plots of RBT_{min} for all the conflict angles based on three different control actions (i.e., SACR, MACR and BOTH) without considering the interaction with



(a) 30° conflict angle



(b) 60° conflict angle



(c) 120° conflict angle

Fig. 12: Box plot of RBT_{min} for all conflict angles.

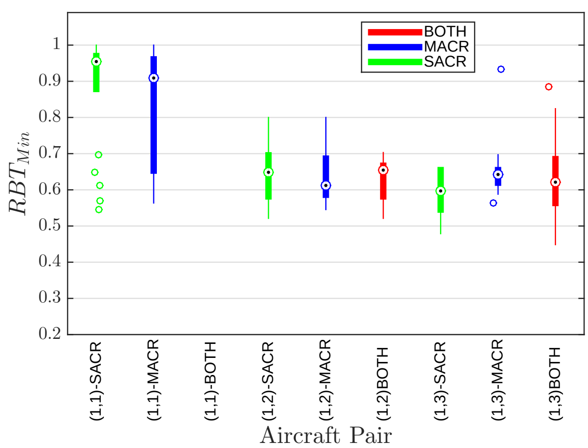
the forbidden zone (no-go area). Here, BOTH means the robustness value when both the control actions (SACR and MACR) were used to resolve the conflict.

It can be observed from Figure 12(a) that the median value for 30° conflic angles for MACR command is slightly more, which suggests that the airspace is more robust when MACR command is used over the other two. The box plot has a larger spread for SACR command whereas for MACR the least RBT_{min} value is always more then SACR command. And the distribution of robustness data for MACR command is compact. As the conflict angle increases, the RBT_{min} for both SACR and MACR commands are almost similar. Although we can notice from Figure 12(b) that even for 60° conflict angle MACR command gives a better median value than SACR command. Finally for 120° conflict angle (Figure 12(c)) SACR command resulted in better robustness value than MACR command, hence proving hypothesis H1.

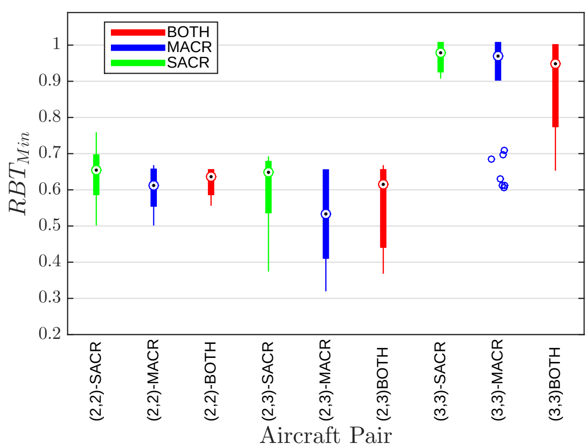
2) Aircraft Pairs (AP): Figure 13(a) shows the box plot of robustness for the first three aircraft pairs i.e., (1,1),(1,2) and (1,3). For (1,3) aircraft pair the RBT_{min} value is better when MACR commands are used. Since the separation between aircraft are less, participants preferred to use MACR commands which makes the airspace more structured and all the aircraft followed the same trajectory. For the other aircraft pairs RBT_{min} (i.e., (1,1) and (1,2)) is better for SACR commands.

Figure 13(b) shows the box plot of RBT_{min} for the last three aircraft pairs i.e., (2,2), (2,3) and (3,3). The median value of RBT_{min} as seen from Figure 13 remains the same in-between 0.7-0.6. But the RBT_{min} for aircraft pair (3,3) is the highest when compared to all the other aircraft pairs with a value close to 1. It is similar for both SACR and MACR commands, since all aircraft fly in single stream one behind the other. If the aircraft from one stream were maneuvered behind the other stream then the RBT_{min} would result in a value close to 1.

A non-parametric test was conducted on the data of RBT_{min} values. A Friedman test was conducted for each of the six aircraft pairs with respect to three conflict angles and the results from the tests are described in Table V. It can be observed from the Friedman test statistics table (Table V)



(a) First three aircraft pairs



(b) Last three aircraft pairs

Fig. 13: Box plot of RBT_{min} for all the aircraft pairs without considering interaction with no-go area.

that the p-value is less than 0.05 for conditions AP1, AP3, AP4, AP5 and AP6 and the RBT_{min} values are significantly different in these conditions. Hence, it can be concluded that there is a significant difference in the value of robustness for aircraft pairs AP1, AP3, AP4, AP5 and AP6.

TABLE V: Friedman Test Statistics[a] for Robustness

Aircraft Pair	Total N	χ^2	df	p-value
AP1-(1,1)	**13**	**8.588**	**2**	**0.014**
AP2-(1,2)	13	2.923	2	0.232
AP3-(1,3)	**13**	**7.569**	**2**	**0.023**
AP4-(2,2)	**13**	**11.231**	**2**	**0.004**
AP5-(2,3)	**13**	**20.32**	**2**	**0**
AP6-(3,3)	**13**	**8.213**	**2**	**0.016**

A post-hoc test was carried out with a Wilcoxon signed-rank test, where a comparison was made between the conflict angles. Since the number of pair-wise comparison here is 3 (i.e., k = 3), therefore the α value (Bonferroni correction of the significance threshold) is changed from 0.05 to 0.016.

TABLE VI: Wilcoxon Signed Ranks test for robustness

AP1-(1,1)	Z	p-value
30° & 60°	**-2.830**	**0.005**
30° & 120°	-1.083	0.279
120° & 60°	-2.197	0.028
AP3-(1,3)	Z	p-value
30° & 60°	-1.888	0.059
30° & 120°	-0.471	0.637
120° & 60°	-1.643	0.100
AP4-(2,2)	Z	p-value
30° & 60°	**-3.181**	**0.001**
30° & 120°	-0.804	0.421
120° & 60°	-2.271	0.023
AP5-(2,3)	Z	p-value
30° & 60°	**-3.180**	**0.001**
30° & 120°	-0.178	0.859
120° & 60°	**-3.181**	**0.001**
AP6-(3,3)	Z	p-value
30° & 60°	**-2.412**	**0.016**
30° & 120°	-1.861	0.063
120° & 60°	0	1.0

The results from the Wilcoxon Signed Rank test for the robustness value is shown in Table VI. It can be noticed that the p-value is less than 0.016 for aircraft pairs AP1, AP4, AP5 and AP6. For AP1 and AP6 the robustness value was significantly different for 60° conflict angle than 30° conflict angle. For AP4 and AP5 the robustness value for 30° conflict angle was significantly different than 60° conflict angle. Also for AP5 the robustness value for 120° conflict angle was significantly different than 60° conflict angle.

D. Added Track Miles

1) Conflict Angle: Since a forbidden zone or a no-go area was present in the airspace, all the aircraft had to deviate from their original trajectory. Therefore, it resulted in all the aircraft flying the extra distance (added track miles).

Figure 14 shows the box plot of extra added track miles (*nm*) with respect to all the conflict angles. It can be noticed that, MACR commands resulted in more track miles than SACR commands for all the conflict angles. Because when a pure MACR command was used for aircraft pairs (1,3) and (3,3), participants had to wait until all the aircraft were inside the airspace and then provide trajectory revision. This meant that the first aircraft which entered the airspace was already close to the forbidden zone, and hence had to deviate more than the last entering aircraft. Therefore, MACR commands resulted in relatively more track miles than SACR commands. The hypothesis H3 was based on the findings from the preliminary experiment. In the preliminary analysis experiment, aircraft had to deviate based on the conflict resolution provided and there was no forbidden zone present. Therefore MACR commands resulted in less added track miles for lower conflict angles than SACR commands.

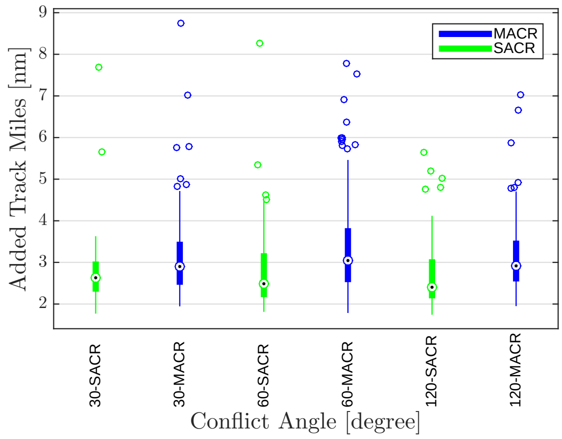
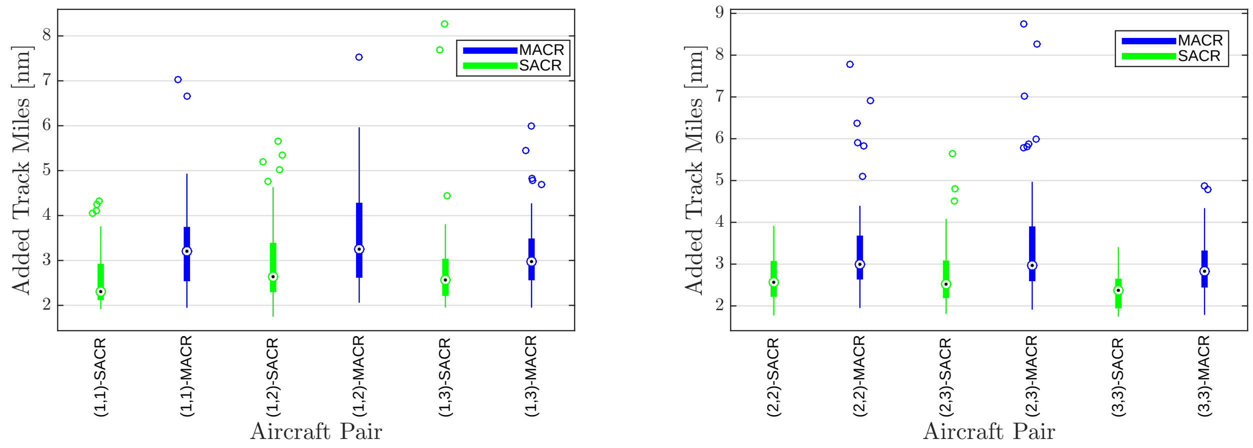


Fig. 14: Added track miles - Conflict Angle.

2) Aircraft Pairs: Figure 15 shows the box plots for the extra added track miles for all the aircraft pairs. As investigated in the analysis for conflict angles, in this case too the track miles are more, when MACR commands are used than SACR commands. The median value is similar for both the commands over all the aircraft pairs.

Figure 16 shows the line plot for added track miles for the aircraft pair (3,3) for all conflict angles for a selected list of participants. For this aircraft pair, all the aircraft flew in a same stream one behind the other which were separated in time (1 *min* 50 *seconds*). It can be noticed that the added track miles are relatively more when MACR commands are used. It can also be noticed from the plots that it fluctuates between peaks and minimum values. This is mainly because of the sudden heading change for the first aircraft in the stream, which will have to deviate a lot more than the last aircraft in the same stream, since the first aircraft will be closer to the forbidden zone.



(a) First three aircraft pairs

(b) Last three aircraft pairs

Fig. 15: Box plot of added track miles for all the aircraft pairs.

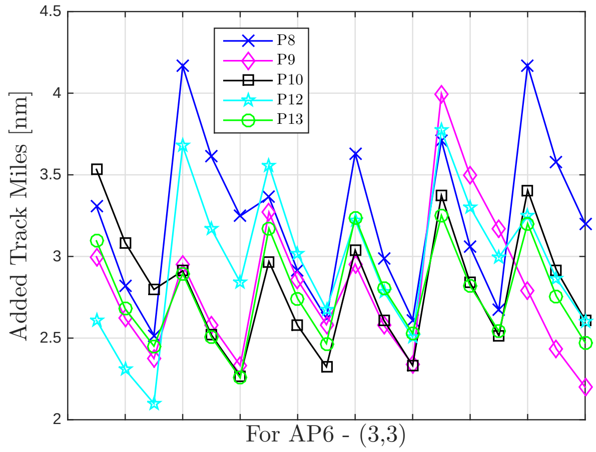


Fig. 16: Line plot of added track miles for AP6 - (3,3).

A non-parametric test was conducted on the data of added track miles. A Friedman test for each of the six aircraft pairs with respect to three conflict angles indicated that the difference between conditions is significant for aircraft pair 3 - (1,3) (AP3 - $\chi^2 = 6, p = 0.05$). A post-hoc test was carried out with a Wilcoxon signed-rank test, where a comparison was made between the conflict angles. Since the number of pair-wise comparison here is 3 (i.e., k = 3), the α value (Bonferroni correction of the significance threshold) is changed from 0.05 to 0.016.

TABLE VII: Wilcoxon Signed Ranks test for added track miles

AP3-(1,3)	Z	p-value
30° & 60°	-1.293	0.196
30° & 120°	-0.943	0.345
120° & 60°	-1.922	0.055

The results from the Wilcoxon Signed Ranks test is shown in Table VII. There was no significant difference between the conflict angles for aircraft pair AP3.

E. Workload

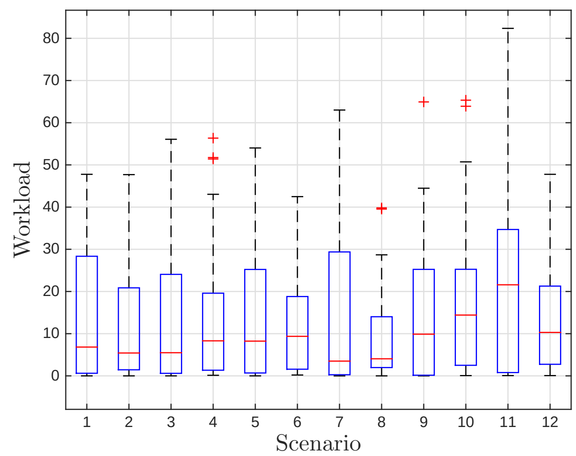


Fig. 17: ISA workload from the participants over twelve scenarios.

The traffic scenario was designed specifically to check the strategies and preference of control action of a participant. Over the six scenarios each participant would have resolved conflicts involving six aircraft pairs with all three conflict angles. At a time, only one aircraft pair would fly into the airspace. Participants had enough time until the next pair of aircraft arrived to think of a strategy and execute that strategy. Therefore there was a lot of dwell period in-between each aircraft pair. A sound was also associated with the workload bar, so that participants received both visual and auditory cues reminding them to click on the ISA workload bar to dismiss it. It can be noticed from the plot shown in Figure 17 that the workload is relatively less in all the scenarios. Since participants had a lot of time in-between traffic, it was possible to asses the situation and come to a solution to resolve the conflict. The experiment was designed in a way such that the participants were not overloaded with tasks (i.e., resolving conflicts and trajectory revisions).

F. Positive and Negative robustness contributions per participant

$\Delta\overline{RBT}_{min}$ value is the difference of average RBT_{min} before the control action and average RBT_{min} after the control action. If the average RBT_{min} was negative then it was considered as (-1 contribution) and if it was a positive then it was considered as (+1 contribution). Figure 18 shows the bar plot of change in minimum trajectory robustness due to controller control actions. The value of RBT_{min} contribution per participant is calculated by the following equation:

$$C = \frac{\sum \text{sign}(\Delta\overline{RBT}_{min})}{N_{cmd}} \tag{2}$$

where,

C = Contribution of RBT_{min} per participant
$\Delta\overline{RBT}_{min}$ = Average RBT_{min} before and after a control action
N_{cmd} = Sum of all the individual control actions (i.e., SACR or MACR)

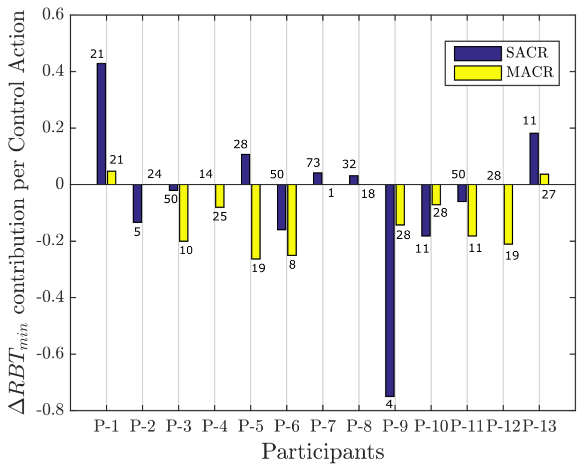


Fig. 18: Bar plot of ΔRBT_{min} contribution per participant

Figure 18 shows the effect of controller actions (SACR or MACR commands) on the overall robustness. Participant 1 executed 42 control actions (21 SACR and MACR commands) and the overall impact of these control actions on the airspace robustness is 0.44. Compared to all the other participants, participant 1 performed the best in terms of preserving more airspace robustness. Whereas participant 13 executed 38 control actions (11 SACR and 27 MACR commands) and its impact on flexibility was 0.18.

It can also be observed from Figure 18 that the overall contribution of using MACR commands resulted in decreasing the overall airspace robustness as compared to SACR commands. The reason for this can most probably be the way in which MACR command was executed. Although participants indicated that they preferred MACR command for aircraft which were close to each other in the same stream and MACR command for inter stream with lower conflict angles. The way in which MACR was used in conjunction with SACR commands had an impact in maintaining a high airspace robustness. Therefore, a combination of best ATC practices and the proper usage of SACR or MACR command according to the traffic situations will result in preserving the airspace with a higher robustness value.

G. Questionnaire Results

Each participant was asked to fill out an online questionnaire form after all the six measurement runs. The questionnaire mainly focused on testing their situational awareness and the type of strategy they would choose in solving traffic situations. Participants were also asked to mention which type of control action they would choose in resolving the conflicts. Participants indicated that they preferred to use MACR commands in all situations, especially when aircraft were close to each other and flying in one single stream. They also expressed that MACR command helped them to make the airspace sector more structured. In situations where MACR was not possible, they commented that, they would opt for using SACR. Hence, it is preferable to have the option of both the commands and not just rely on either one of them for conflict resolution.

One participant stated, *"MACR makes aircraft in sequence or two columns of aircraft in sequence easier to control. Once it gets more busy or once I make a mistake, I would still need SACR to make some quick, agile adjustments".* Participants also indicated that the use of MACR commands for aircraft from different stream was sometimes tricky due the presence of a forbidden zone. They had to use trial and error method of placing the intermediate way-point and check if any of the aircraft trajectories were still intersecting the forbidden zone. Nonetheless, the participants indicated that they would use MACR command for inter-stream aircraft, only for lower conflict angles. For higher conflict angles the revised trajectory would result in almost head-on and they wanted to avoid head-on trajectories. They also expressed that the Travel Space Representation (TSR) was very helpful in terms of understanding the interaction of traffic. All participants commented that the workload in the entire experiment run was relatively less, because the traffic structure was not complex, and enough time was available to think and execute a strategy.

V. Discussion and Recommendations

An experiment was conducted to measure whether MACR command was beneficial in terms of safety and efficiency compared to SACR command. Results indicated that MACR is better than SACR only under specific conditions (traffic structure). Robustness (RBT_{min}) is dependent on the interaction of aircraft within the airspace. At lower conflict angles the value of RBT_{min} is slightly better when MACR commands are used over SACR. But as the conflict angle is increased the RBT_{min} value for both the commands were found to be similar. MACR commands would be used for complex situations and also to make the airspace more structured. Only for aircraft pair (1,3) the robustness value was better when MACR command was used. For all other aircraft pairs SACR command resulted in a better value. For aircraft pairs (1,1) and (3,3) the robustness value (irrespective of the command) was close to 1. This is due the fact that these aircraft (AP6-(3,3)) would be flying in the same stream close to each other.

In terms of efficiency (added track miles) MACR command resulted in more added track miles than SACR. Because, a forbidden (no-fly) zone was present in the airspace sector. Between the entries of any aircraft pair in the airspace, a dwell period was introduced. Before the next pair entered, the first aircraft pair would have already passed halfway into the sector. Hence, there was enough time in-between two aircraft pairs for the controllers to work out a strategy. Therefore, the results showed that workload in all the scenarios was relatively less. Since, the research focus was mainly to investigate the strategy involved in conflict resolution, the workload data is of less significance in this research.

Using MACR command to resolve conflicts for aircraft flying in different streams (inter-stream) and with higher conflict angles will result in all the aircraft flying towards a common way-point (merge points) head on. This will create chock points for the projection of traffic. Thereby effecting the overall robustness of the airspace.

The current operation of MACR command is such that the penalty of flying extra track miles (*nm*) is equally shared between all the aircraft involved in the conflict. But with respect to airline or a pilot it might be fair to deviate other aircraft with respect to their own. The definition of fairness depends on the perspective of each stake holder (i.e,. airline, pilot and ATC). Hence, even though mathematically the burden is shared equally, the economy of flying should also be considered while executing a MACR command. This research study did not take into consideration the economics and therefore fairness should be properly defined with all the factors considered. Therefore the current MACR capability is not ideal for conflict resolution in real life operations.

Based on the outcome from this experiment, for future research the following recommendations are suggested. Current implementation of MACR 4D interface allows only the manipulation of those aircraft which are inside the airspace sector. If the controller already knows the direction of travel of aircraft, the controller should be able to execute trajectory changes to those aircraft which are yet to enter the airspace sector. This will be convenient when more aircraft are flying in the stream. Since they are already sufficiently separated, the controller can select all the aircraft using MACR command and resolve the conflicts. In doing so, all aircraft will fly towards the new way-point (merge point) as soon as they enter the airspace. In the current interface, the aircraft at the front has to undergo more heading change which will result in longer track length than the last aircraft.

Current implementation of MACR is such that the controller has to use trial and error method to make sure that the trajectories are not intersecting the forbidden zone (if present in the airspace) while placing an intermediate way-point for aircraft flying from two different streams. This can be improved over experience, but if the trajectories are attached to the way-point cursor like the way-point symbol (holding ctrl button), controllers can intuitively know how the new trajectory would be, rather than checking it by placing the new way-point, thereby eliminating one step.

When working with multiple aircraft flying in from different streams, the software will check whether they arrive at that point at different times to keep them separated. But sometimes the aircraft will fly close to each other (depending on the choice of the way-point) and more often they will usually fly on a 'conflict' course (head on). This means that in order to keep things safe, and without the possibility of any glitches in the software, monitoring time will be especially high until this conflict pair has been entirely resolved. It is suggested to have two way-points (when working with two a/c coming from different streams and that are already self separated), closely located which will not only separate the aircraft in time but also in position. This configuration will result in both the aircraft flying in a round about fashion which will increase flexibility, and also result in both aircraft flying more distance than usual, but as a benefit it will decrease the monitoring time of the controller (mental load).

Finally, it will be interesting to investigate the results when a more complex traffic situation is designed. For this experiment the airspace design was symmetrical. The forbidden zone was placed at the center of the airspace. And only one aircraft type was considered. The interface also did not consider any uncertainties while executing trajectory revisions. This will not be the case always in real life. Therefore it will be interesting to investigate the effect on efficiency and safety when a diverse traffic mix of aircraft are considered. And also conduct an experiment considering only expert controllers as participants. The novice controllers in this experiment completely trusted the software while resolving conflicts, where as expert controllers might not rely on the automated system as much as novices.

VI. Conclusion

The objective of this research is concentrated on using the concepts of Trajectory Based Operations (TBO). The interface uses TSR form, that allows the controller to organize and manipulate 4D trajectories of multiple aircraft concurrently. The robustness metric used, integrates the available airspace of the aircraft with separation constraints of other traffic, enabling the controller to check if the resolution action can absorb uncertainties (free from disturbances). Using the results from the preliminary analysis as a baseline, a final human-in-the-loop experiment was conducted to investigate which control options the controller will prefer while resolving the conflicts.

Results from the experiment suggested that the new control action (MACR) which was made available for this research was beneficial in terms of maintaining airspace structure and robustness. And all the participants expressed that the MACR command was helpful while manipulating trajectories of more than one aircraft with only one control action. But MACR was not always helpful or preferred, because at higher conflict angles using MACR would result in head-on trajectories which controllers try to avoid. In such situation participants mentioned to have both options available for conflict resolution.

Therefore, it is concluded that a combination of both control actions (i.e., SACR and MACR) used in the correct manner will result in an airspace which is more robust (safe) and more efficient. Obviously, some trade offs need to be done with respect to which control action a controller chooses, since both options have their own benefits and disadvantages. Future research should focus on improving the interface capabilities so that the development will eventually make our skies safer and more efficient in the future.

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PART- II

THESIS BOOK OF APPENDICES

A

Literature Review

This literature review appendix summarizes all the research and findings which are relevant and helpful for this thesis assignment. In Section A.1 the definition and working of 4D trajectory is explained, in Section A.2 understanding ATC control action/decisions about best practices for CD&R. In Section A.3, principle of travel space representation and research related to TSR and previous experiments conducted on this topic is explained. In Section A.4, robustness metric is defined explaining its significance for this thesis assignment. Finally in Section A.6 importance of co-operative management is described.

A.1 4D Trajectory

The Air Traffic Management (ATM) domain in Europe and USA will undergo a growth of three times the current demand[15]. In order to cope with this growth, time based-shared 4D trajectories are generated. The objective here is to enhance efficiency of air travel from "check-in to check-out" [15]. "Three dimensions in space (latitude, longitude and altitude) and time, together define a 4D trajectory of an aircraft" [15]. This 4D trajectory will be generated by the on-board flight management system (FMS), using this data, the current state can be unambiguously interpreted on the ground using high speed data links [15]. The aircraft has to fly from point A to point B within a set time interval (controlled time-of-arrivals (CTAs)). A vast amount of data will be exchanged between the aircraft and controller which is time consuming to interpret manually, therefore voice communication will become a bottleneck. The data link becomes even more crucial in order to compensate for the growth. Data transferred should be redundant and unambiguous, meaning no further interpretation or assumptions must be needed to use this received data [15]. Airborne Separation Assistance Systems (ASAS) utilizes ADS-B data to predict aircraft trajectory, weather cells, terrain information etc, using this info, tasks such as self separation can be delegated to the flight crew, maximizing the capabilities of avionics systems in the aircraft. Entire 4D Trajectory information will be accessible to the concerned parties via System-Wide Information Management (SWIM), which will facilitate the overall traffic flow, and arrival management. As explained earlier, since time is considered as an explicit variable, other parameter such as Required Time of Arrival (RTA) and the FMS trajectory can be advantageous for early users and can also be a selling point to attract more airlines to incorporate this technology.

For implementing 4D trajectory the following prerequisites must be fulfilled:

- For every trajectory revision (renegotiation of trajectory), a new 4D trajectory will be generated
- Commands such as heading change, course, vertical trajectory, speed and even altitude changes, which are difficult to be transferred without assumptions directly into a 4D trajectory update should be discontinued
- Data should be redundant and common data set must be maintained since there will be no voice communication
- Data exchanged should be unambiguous

This envisioned system will allow the aircraft to fly in any desired trajectories (planned trajectory) without the intervention from ATC, unless there are any undesirable events such as conflicts, weather cell disruptions or system failures. This "control by exception" [15] will allow all the players (Airline Operations Center (AOC) and Air Traffic Service Providers (ATSPs)) to negotiate their respective 4D trajectory prior to the flight and then execute their preferred plans. The human operator is supported by Decision Support Tools (DSTs) in order to increase the efficiency in the prediction of 4D Trajectory.

In order for 4D Trajectory to be feasible, the following requirements have to be met:

1. The FMS on-board the flight should be capable of optimizing and generating the FMS trajectory. This generated trajectory must be available to all the users, external of the FMS.
2. The FMS trajectory should be broadcast using a data-link from the aircraft.
3. ATM must be capable of receiving this data, which will be sufficient to distinguish each individual movement (proper defaults and back ups).
4. Conflict resolution needs to be either in the form of trajectory constraints, or as alternative trajectories.
5. FMS on-board the aircraft should have the capability to accept this trajectory revision generated by the ATC or re-plan its trajectory accordingly (on basis of the received command from ATC).

As explained in the above sections, 4D trajectory convey the "air traffic controllers (ATCo) intent to fly in any direction" [15]. The goal here is to choose a trajectory with least costs (least amount of fuel used, shorter distance to fly, less turbulent etc). In fact it is not simple to make sure all these parameters are fulfilled. Therefore, in order to optimize one parameter the others have to be compromised, hence weighting factors are assigned to each parameter and a final optimum trajectory is selected which will result in maximum revenue. The vital factor which is hampering the current centralized ATC system to work to its full potential is the deficit in accurate positioning and intent information. The answer for this problem is a "distributed ATM system", this system will integrate both its own information with the redundant navigation info from the aircraft in order to generate 4D trajectories, estimated time of arrival (ETAs) and when required for capacity reasons, required Time of Arrival (RTAs).

A.1.1 Airspace Structure

The performance of a controller depends on the complexity of airspace. Histon et al., in an experiment found that airspace structure is one of the prime factors which has a direct impact on "controller cognitive complexity" and based on airspace, the controller will make simple abstractions by having a mental model about the airspace and perform the task accordingly. A main factor which is restricting the growth and capacity of Air Traffic Control (ATC) system is "Cognitive Complexity" [1]. The strategies employed by the controller to minimize cognitive complexity depends on the airspace structure which is being handled. The cognitive load on the controller and airspace complexity are directly proportional. Which means, if the airspace structure is more complex, the cognitive load endured by the air traffic controller will also increase.

$$Cognitive\ Mental\ Load \propto Airspace\ Complexity \tag{A.1}$$

Structure-based abstractions are a set of controller's internalization which influences the way in which the controller commands an aircraft. It is the simplified pattern which reduces the perceived complexity of an airspace structure, which makes it easy to predict the future traffic situations. There can be more than one structure based abstractions present in the mental model of a controller for a particular airspace sector. The use of structure-based abstractions will depend on the task and goal for a given airspace. Based on observation, the structure-based abstraction are divided into four types:

- Standard flow
- Critical flow

- Grouping abstractions
- Responsibility abstractions

Standard flow are nothing but normal abstractions made by a ATCo for aircraft to fly in an airspace, this abstraction is used the most by ATCo. Common aircraft type, aircraft flying in the same path etc., are considered as standard flows. An aircraft flying a unique route in the airspace sector can be considered as "non-standard" flow. Critical points are the points in an airspace where two standard aircraft flow streams merge together to form a single stream, or a crossing point between two separate standard flow streams. Similarly, in certain cases where standard flow is absent, in order to reduce the complexity of an airspace sector, an ATCo can group a set of aircraft which share some common properties. For instance when two or more aircraft have a common heading and speed, destination etc. These two aircraft can then be addressed as a single entity, managing the heading together. Rerouting a set of aircraft around a weather cell is also another example. Grouping of aircrafts may occur while approaching a critical point. This can be visualized from Figure A.1.

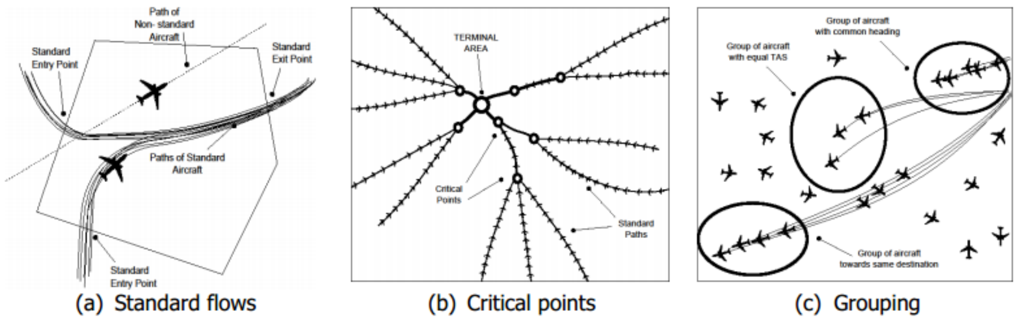


Figure A.1: Types of Structure Based Abstractions, (adapted from Histon, 2002)[1].

Now let us discuss structure-based abstractions in 4D trajectory manipulation. Many important features such as controller actions to keep the number of CTA and updating new CTAs, the resolution maneuver and number of CTA for a sector, still needs to be decided and fixed (regulated) [1]. However, the concept of adhering to time constraints within an airspace sector is well established. Introducing 4D trajectory will most probably alter the manner in which current abstractions are used by ATCo. Due to the fact that, traffic will no longer be predictable, crossing and merge points to a standardized locations in a sector might be absent altogether. Therefore, the consequence of this can be a higher cognitive complexity. Nevertheless, operators can create new forms of structure-based abstractions in 4D trajectory. Controllers can include time into their working mental model. This paves way for "time based decision support tools" which aids the ATCo, therefore extending their ability while resolving conflicts. Similarities between controlled time of arrival and critical points can further simplify the airspace sector. If an aircraft has multiple CTA's, disruption in any one CTA (not able to meet a CTA) will automatically have a domino effect in meeting other CTA's. This increases the complexity (degree of freedom) in the mental model of a ATCo. Perhaps limiting the number of CTA's for one aircraft might be a solution. But this might hamper the overall efficiency in meeting the independent CTA's. Speed change, altitude changes, heading changes etc., are a few resolution maneuvers which aircraft must be free to employ in order to meet the CTA. The timing of these maneuvers further adds to the variability. This eliminates the sense of predicting the future position of aircraft. This makes it ever more tough to model the aircraft behavior. Workload for the controller will increase because they can no longer use simple abstractions to visualize the projection of traffic.

Nonetheless, this can be mitigated by restricting the aircraft maneuvers (speed only or lateral only). This will streamline the dynamics of a controller. In the initial stages when 4D trajectory is introduced, a controller could be handling a blend of aircraft, like traditional aircraft and aircraft with 4D trajectory capability. This will create a "mixed equipage problem" [1]. In these situations, the controller has to tune his mental model in order to handle the increased degree of freedom with various dynamics in communication, surveillance and navigation capability of an aircraft. Controller has to individually track the aircraft which also increases the workload. One solution for this is to differentiate aircraft with 4DT capability and traditional ones (equipage level) by ordering them to fly in different altitudes. This will shrink the workload for a controller working mental model. Histon et al., conducted an experiment which compared time-based operation (4DT) with position-based operation (current operations) to measure the cognitive complexity. Simulations consisted of a generic arrival airspace with multiple merge points with one metering fix point. A HITL experiment was conducted by creating a fast time simulation. Results indicated that 4DT operations improved controller performance, and all the participants perceived reduced complexity when compared to position-based control, which showed the advantage of time-based control over position-based control [1].

In a study conducted by Histon et al., airspace design was found to be second most important aspect in complexity factor behind traffic volume [2]. Using Enhanced Traffic Management System (ETMS) the traffic patterns/flow of 24 *hours* over Boston airspace were analyzed to check, which airspace structure (shape/design) was perceived as easy or difficult by air traffic controllers. This result will be used while designing the final HITL experiment for this research.

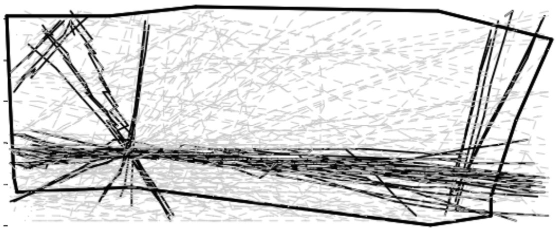


Figure A.2: Traffic flow felt as easy for ATCo

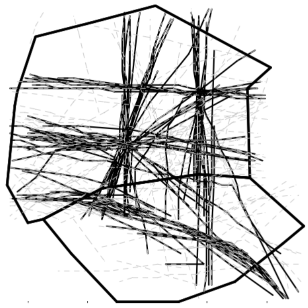


Figure A.3: Traffic flow felt hard for ATCo

Figure A.4: Traffic flow data of 24 hours from ETMS [2].

Controllers were persistent to point out that they concentrated equally on aircraft which were yet to enter their sector along with active aircraft which were already present inside the sector[2]. This suggested that controllers perceived boundary of control propagates beyond the assigned sector boundary. This is termed as "area of regard", therefore aircraft which are yet to enter the sector were deemed equally important along with aircraft which were currently inside the sector and influenced the decisions of the ATCo.

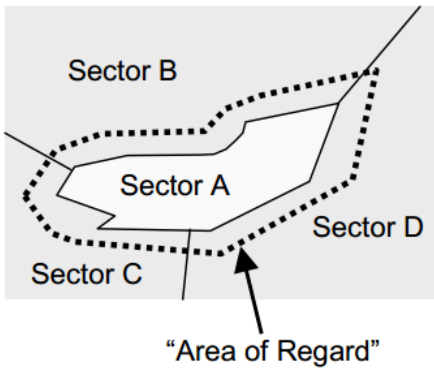


Figure A.5: Area of regard as perceived by controller, (adapted from Histon et al.,) [2].

A.2 Conflict Detection & Resolution (CD&R)

To understand the effects of structure on complexity Pawlak et al,. [16] identified four key processes in conflict resolution for air traffic control (ATCo), they are:

- Planning
- Implementing
- Monitoring
- Evaluating

In the planning phase, a controller makes sure that the traffic in the airspace moves in a conflict free manner by a series of control actions within the constraints for a given sector. Implementing is the next phase where the actual performance of the control actions is required. In monitoring phase the controller monitors current traffic state and the future predicted traffic state, observing if the control-actions implemented are conforming as expected. And in the evaluating phase the controller verifies overall efficacy of the control actions in conforming to all the constraints and goals corresponding with the sector. The ability to predict future traffic states is an important skill for a controller. It is thought that structure-based abstractions decreases the perceived complexity of a sector which also makes the decision making process of the controller straightforward.

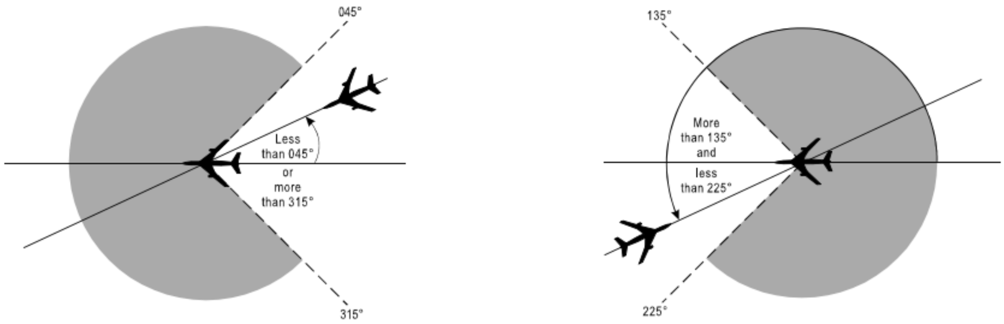
Conflict Detection and Resolution (CD&R) corresponds to the majority of mental-load for an ATCo [10]. In order to minimize the mental load endured while detecting a conflict, controller has to make decisions which relieve themselves from enduring more workload. Therefore, a controller best practice (good or bad decision) has a lot of significance and has a direct impact on the change in workload. In the following sections these best practices for ATCo will be discussed.

During conflict detection these are the most important steps taken by the air traffic controller, 1) Scan for conflicts in the airspace sector (aircraft pairs in conflict) and 2) Resolve the detected conflict at the right time with minimum loss of time and energy (monitoring time). In an interview conducted by Kirwan et al., and his colleagues, they found that, when controllers scan for any possible conflicts in the airspace sector, they generally do so with a look ahead time of 5-10 *minutes* [10]. The aircraft pairs in conflict within this look ahead time (5-10 *minutes*), under high workload conditions, controllers are reserved with respect to delegating the control actions. Therefore any disparity in terms of separation between aircraft, controllers are quick to judge the pair as conflict under high workload conditions. Workload experienced might be high in that instant, but most probably regulates over a long run because the monitoring time of the conflict pair will reduce [17]. As soon as a conflict is detected, the natural tendency is to resolve it swiftly and efficiently. Dittmann et al., in an experiment interviewed several controller (talk loud sessions) and noticed that controllers exercised a wait & decide strategy to see how the traffic projects under low-medium workload conditions instead of acting immediately to resolve the conflict [9]. It is understandable that, by employing this strategy, the controllers will eventually come to an optimal (refined) solution to resolve the conflict. But on the flip-side, controller is subjected to extended monitoring of conflict pair. Therefore, on the contrary this cognitive resource could have been allocated to other tasks [9]. It was also found that in high workload conditions, controller rarely or even never uses this strategy. Control actions were executed instantly after the conflict detection [9].

Rantanen et al., studied radar data to measure the urgency of controller actions and found that ATCo judge conflicts distinctly (distance and closure rate), which they labeled it as "distance over speed bias" [13]. ATCo segregate the urgency of conflict depending on the relative distance between the aircraft pair over closure rate. This means, priority is given to that aircraft pair (conflict) which are close to each other, even though the closure rate is small. And the aircraft pair (conflict) with relatively large distance but rapid closure rate is recognized as less critical [13].

ATCo undergo extensive training before handling real traffic situations. During this period they learn the standard practices (solutions) for each conflict type. Therefore, not every solution needs to be reasoned from scratch [9]. The controller stores all the standard solutions for simple conflict type in their "cognitive (metal) library" [9]. This library aids the ATCo in arriving at a control action with minimum strain on their cognitive resource. Kallus et al., in his research also noticed that controllers were quick in concluding/selecting a control action during high workload. Controllers preferred safe solution and hurried the control actions over efficient solutions. Although on a short term such procedure may benefit and diminish the workload, but on a long term it will eventually increase the workload because, the solution (control action) arrived during that stage did not contemplate all the factors necessary to derive an optimal solution. Della Rocca et al., in a similar experiment also noticed that in high workload conditions, controllers often choose the first solution which they thought of and were less inclined to play the "wait and see" strategy [11]. This effect was more dominant for terminal controllers than for en-route controllers. Therefore, expert ATCo were more inclined towards control actions which warranted the lowest workload, least monitoring time, less number of aircraft manipulated (heading change and additional track miles flown) and arrive at a control action quickly and further fine tune it later [13] [10].

Kirwan et al., found that controllers usually made slower aircraft go behind the faster aircraft for acute angle conflicts. Whereas for conflicts that were less than 45°, faster aircraft was directed in front of the slower aircraft. He also investigated if ATCo adopted a "Pairwise strategy" [10]. Which meant, if controllers considered only the aircraft which were in conflict, or an overall approach in which other aircraft in the sector were also considered while choosing a strategy to resolve the conflict. During talk-loud sessions it was observed that, initially controllers indeed adopted a pairwise approach and later checked whether this control action would introduce any new secondary conflicts. The identified best practices are summarized in the below table which will be used as a baseline for the preliminary analysis in this thesis assignment.



(a) Acute Angle conflict

(b) Obtuse angle conflict

Figure A.6: Conflict angle classification used by ICAO (International Civil Aviation Organization,1996).

No	Best Practices by Air Traffic Controller (ATCo)	Workload condition
	Conflict Detection	
1	Look ahead time 5-10 minutes	
2	More timid with segregating conflicts	High
3	Wait and see strategy	Low or Medium
4	Instant action after conflict detection	High
	Conflict Resolution	
5	Training and experience aids the controller in building the mental library	
6	More timid with segregating conflicts under which reduces efficiency	High
7	Use of standard and regular solutions	High
8	First solution that the controller thought	High
9	Selecting resolution which requires less amount of monitoring	
10	Selecting resolution which requires less amount of co-ordination	
11	Selecting resolution which has the least manipulation (least number of aircraft move, min additional track miles flown)	
12	Arrive at a control action quickly and further tune it later	
13	Make the slower aircraft go behind faster aircraft (acute angle conflict)	
14	Faster aircraft in front of slower aircraft for conflicts with less than 45°	
15	Solve the conflict using "pairwise" strategy at first and later check for secondary conflicts	

Table A.1: Best Practices by Air Traffic Controller (ATCo), adapted from M. IJtsma [9–13].

Pilots prefer vertical maneuvers over lateral ones [13]. However there is insufficient data with respect to which maneuver ATCo decides for what conflict geometry. ATCo are more concerned about the overall traffic structure and its future projection. Managing their workload adequately and not over burdening themselves is crucial in preserving high performance. "Expected Utility (EU)" [13] influences a controller to instruct one type of maneuver over another, there are three EU:

- Expediency: control actions which resolves the conflict swiftly are favored over time intensive ones
- control actions which results in the least number of aircraft manipulated are preferred
- Mental-model conformance (visualization): control actions which can be easily perceived on the ATCo traffic display are preferred

When an aircraft is provided with lateral trajectory revision it is more disturbing (disrupts overall traffic) when compared to vertical maneuvers. Because lateral maneuvers require more attention (monitoring) for extended period of time from the ATCo [13]. But longitudinal maneuvers have there own disadvantages, it is troublesome for ATCo to visualize longitudinal maneuver on the plan view display (PVD). Lateral maneuvers whereas on the other hand are straightforward and clear since the PVD are graphically represented. Vertical maneuvers requires ATCo to constantly monitor and understand the numerical altitude data in the aircraft data blocks. Rantanen et al., conducted an experiment to check which maneuvers ATCo prefer, they collected data from 495 en-route controllers and measured the responses. Analyses which was reported included with a total of 256 cases of conflict avoidance maneuvers. Results showed that the most preferred maneuver was level-offs (44%) followed by turns (32%), descents (18%), and climbs (5%). Turns occurred much less frequently than vertical trajectory changes (32% vs. 68%).

Climb is the least favored maneuver because the aircraft has to climb going against gravity which would lead to more fuel burn. Whereas descent exploits gravity. Turns would require a change in speed. This result explains the best and safe ATC practices. Expert ATCo are well aware and diligent about the efficiency and economy of flights under their control. Also as explained earlier, vertical maneuvers (descent in particular) might be withing the planned trajectory of the aircraft, whereas lateral maneuvers is more demanding where ATCo has to re-route the aircraft to its original trajectory after conflict resolution. Therefore vertical maneuvers relieve ATCo from "attention and memory intensive task" [13]. However in this thesis assignment the multi-aircraft conflict resolution, despite restricted to only lateral maneuvering capability, it does not require the controller to re-route any traffic after conflict resolution. Because the interface is designed in such a way that the flight will deviate to its original trajectory after conflict resolution. The interface also uses good visualization from which the ATCo can readily discern the projection of traffic. The interface uses Travel Space Representation (TSR) to visualize the change in traffic. How TSR is effective and further explanation about the TSR is given in the sections below.

A.3 Travel Space Representation

In order to accommodate the increase in airspace capacity, future technologies along with flexibility and diversity, must have the capability to allow an aircraft to fly any routes with more accuracy and strictly adhere to these routes. This shift is foreseen not just on the ground side (ATM side) but also with the in-flight trajectory planning. Therefore the envisioned future ATM systems will be equipped with a capability to plan,implement and execute a flight plan in four dimensions (4D) [3]. Way-points are points which can be added, moved, removed or changed from the interface (display). They are the points which signify the entry-exit point for a flight in the given airspace sector. ATCo will be able to edit them to make any changes in the flight plan. 4D interface used in this thesis assignment will be using Travel Space Representation in its core form. Before understanding the results from this experiment, let us understand the basic working principle of the Travel Space Representation.

4D trajectory will have, space (3 co-ordinates) and time incorporated as constraints. Visualization of flight plan in the 4D trajectory interface will be based on an ellipse [3]. "Ellipse can be defined as a plane in which when two points are traced on this plane, the sum of distance of these two points is constant irrespective of any point on the plane". Let us consider a hypothetical situation, three way-points A, B and C as shown in Figure A.7. A and C are the focal points and B is the middle way-point on the curve of the ellipse. The total distance from AB and BC remains same as long as point B is on the curve of the ellipse. Point B' is located outside the curve of the ellipse, in this case the distance from A to C is increased. Similarly any point B" which is inside the curve will decrease the total distance from A to C. This simple principle spanned by three points on an ellipse can clearly represent both spatial and temporal changes, just by altering the position of the way-points on the interface, required to show the modification in the flight plan.

Any changes in the position of point B (inside or outside of the ellipse), without any speed changes will indicate if the flight will either arrive early or late to its exit way-point. Therefore, with speed changes incorporated into the interface, any point closer to the outside curve, flight has to fly faster in order to adhere to its time constraint to arrive within its alloted required time of arrival (RTA). The speed of aircraft increases as the point B gets closer to the outside curve of the ellipse. TSR interface which is used in this thesis assignment has also included turn characteristics of each aircraft. Therefore, it compensates for aircraft dynamics & provides a visualization of safe area of travel on the display interface.

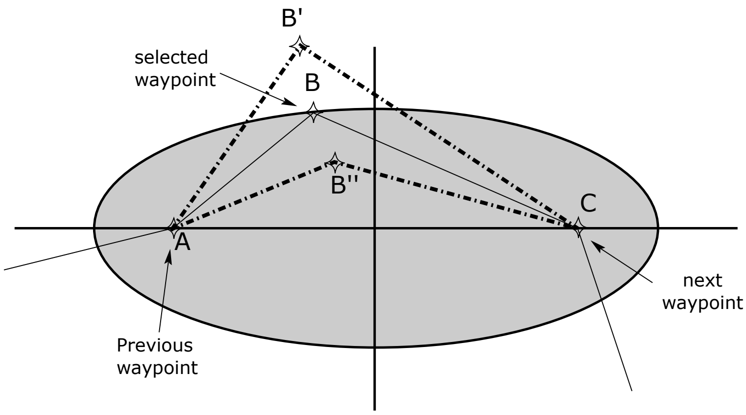


Figure A.7: Travel Space represented as an ellipse, (adapted from Mulder et al.,) [3].

Mulder et al., conducted an experiment using this prototype interface. It was used as a flight plan editor in flight management system (FMS) on the command display unit (CDU). The experiment was conducted at TU Delft ATM lab. In this experimental evaluation, two scenarios with varying levels of complexity for the flight plan was considered. There were also three different levels of interface detail namely, low, medium and high. The results showed that medium and high detail interface were easy and fast to use for the pilots participating in the experiment, and contributed for better task performance [3].

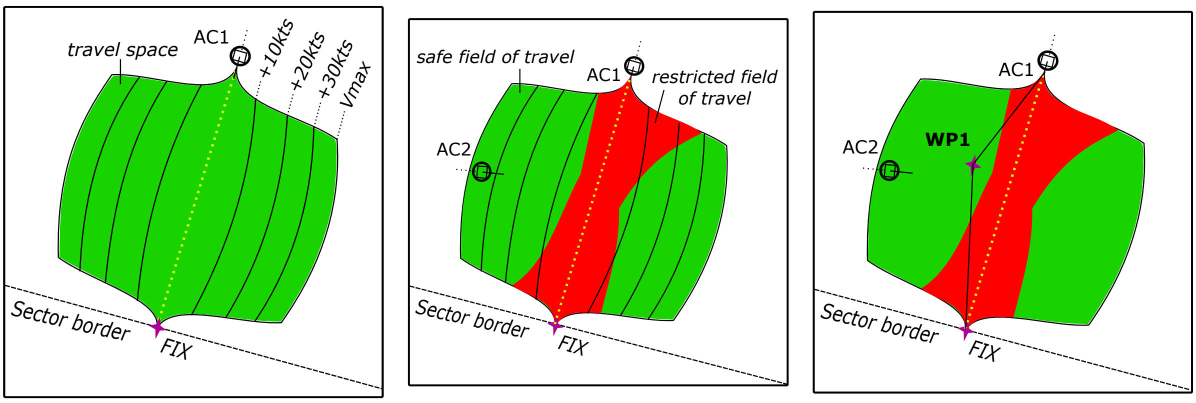


Figure A.8: TSR for one aircraft in the airspace

Figure A.9: TSR when another aircraft enters the airspace (conflict)

Figure A.10: Intermediate way-point is placed to avoid conflict

Figure A.11: Single-aircraft conflict resolution using TSR [4].

The TSR in its simple form having single-aircraft conflict resolution capability is shown in Figure A.11 [4]. The aircraft shown in the sector will have to adhere to strict time constraints within the airspace sector boundary. TSR for aircraft (AC1) is shown in Figure A.8. The size of travel space depends on the speed characteristics of the aircraft. In the next sub figure (Figure A.9), another aircraft (AC2) enters the airspace. TSR for AC1 changes from being all green to a red band (no-go) area in the center. This is due to the fact that, AC1 is in a potential conflict with AC2. If both the aircraft continue flying in this trajectory a collision is imminent. In the next sub figure an intermediate way-point is placed on the green part of TSR of AC1 (go area). The conflict will not be removed if the intermediate way-point is placed within the red-band (no-go) area. The operator can press enter to accept this new way-point. The trajectory is automatically changed and the airspace sector will become conflict free (Figure A.10).

Klomp et al., evaluated this early prototype design by conducting validation experiment. This validation acted as a baseline in order to further fine tune the interface. It was implemented as a computer application and certain distinct traffic scenarios were designed based on real world data. The shape of this airspace sector was based upon the southern part of the "Maastricht Upper Area Control (MUAC) airspace, the Brussels Upper Information Region (UIR) [4]". The results from this validation showed that, the prototype interface would be beneficial for novice operators for their training, which clearly indicated the deviation of flight (heading or speed changes) from the original trajectory. Participants also pointed out that expert controllers will not benefit from this representation. The also suggested that the optimal solutions should concentrate on providing a robust resolution rater than concentrating only on cost and efficiency. More on robustness will be explained in the coming sections. Overall the TSR proved that it would be beneficial in representing the projection of aircraft 4D trajectory.

In another different study, Klomp et al., studied the effectiveness of TSR under varying airspace (i.e structured vs unstructured) and traffic conditions. It also had two experiment condition, one a manual control task with no automation support, and another with automation support. On controller's request, the tool would suggest an automatic trajectory resolution [14]. They also measured the frequency of advisories request and acceptance of the automated resolution. Totally there were six experimental conditions (Note: TS is Structured traffic, TU is Unstructured traffic, PS is small perturbation, PM is medium perturbation and PL is large perturbation).

Table A.2: Experimental condition for TSR interface evaluation, (adapted from klomp et al.,) [14].

Condition	Structure	Perturbation
TS-PS	Structured	Small
TS-PM	Structured	Medium
TS-PL	Structured	Large
TU-PS	UnStructured	Small
TU-PM	UnStructured	Medium
TU-PL	UnStructured	Large

The results showed that, the interface was successful in representing the 4D trajectory and all participants recognized the tool and found it supportive. Workload was found to be high for unstructured condition, but the participants thought it was manageable. Overall the interface proved to be a handy tool in order to aid the controller in tactical revision of 4D trajectory of an aircraft. This TSR interface is used for the final experiment in this thesis assignment, the only difference being instead of single-aircraft conflict resolution, it will also have the capability of multi-aircraft conflict resolution. Meaning the controller will be able to manipulate the trajectories of both/all the aircraft involved in the conflict.

The best practices employed by novice and expert controllers were different. Understanding this difference is key while designing the final traffic scenario for this thesis assignment. The experiment using the TSR has proved that expert controllers provide more consistent and robust control actions compared to novice controllers [14].

Novice: controllers build up their mental library by experience. During training phase, amount of past experience to handle a definite conflict situation might not be sufficient in order to provide a more robust resolution. Due to their limited scope, novice controller will employ a short-term control action without considering the implications on a broader system level (future). By aiding the novice controller to better visualize the robustness change could encourage them to provide more expert like control actions.

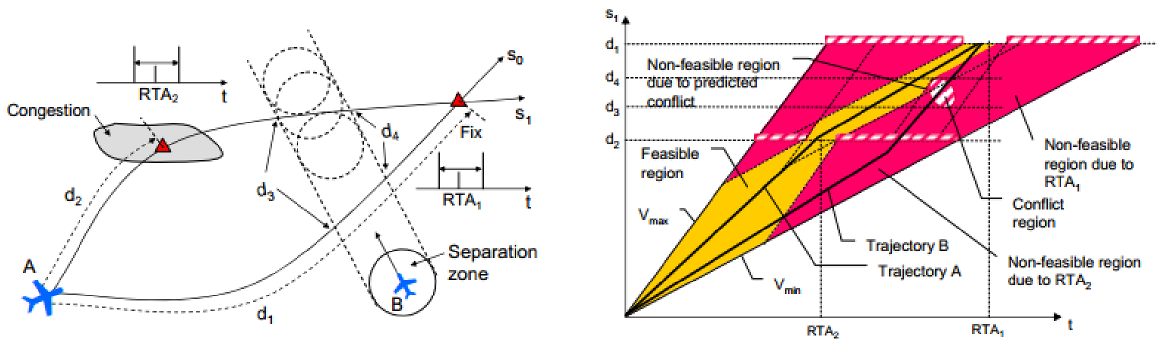
Expert: controller as explained earlier, thanks to their vast experience, they will have a much deeper understanding of every situation no matter how complex. The visualization aid which the TSR provides will be used to validate the control actions which expert controller decides. It was also found that expert controllers are pro-active in terms of the decision making, planning multiple steps ahead in time and set aside addition separation buffers to cope with uncertainties [8]. Controller in this assignment will have the capability of controlling/manipulating more than one aircraft at a time (higher level structure-based abstractions). Which is predicted to reduce workload and traffic complexity.

A.4 Trajectory Flexibility Preservation Function (Robustness)

The ability of a system to absorb disturbance, and to re-organize itself, which does not alter the core function yet maintaining the same structure and identity i.e., immune to disturbance, such a system is called a resilient system [18]. In distributed ATM the primary task of separation assurance is equally shared among air traffic controller and pilots. Numerous methods are available to provide assistance to pilot on conflict resolution, one such method which will be used in this thesis assignment is the trajectory flexibility preservation function [5]. Idris et al., has deduced a metric using which the flexibility of an airspace can be quantitatively measured. A system should be capable of handling disturbances. Trajectory flexibility preservation plans the trajectories in a reasonable way that accommodates for disturbances. Disturbances such as weather cells, other aircraft traffic etc. In a conflict scenario, there are multiple ways for a controller to rid the airspace sector from conflicts. They will select the solution which affords the aircraft with more flexibility. Flexibility is defined as the ability of a trajectory to compensate future disturbances. Flexibility is again divided into two characteristics, Robustness and Adaptability [5].

1. **Robustness**: despite the occurrence of a disturbance, the aircraft ability to keep its current trajectory unchanged is called robustness [5]. (relative number of feasible trajectories)

2. **Adaptability**: whenever there is a disturbance in the airspace, the ability of the aircraft to shift its current trajectory in order to compensate for the disturbance occurred, which has rendered the current trajectory infeasible is called adaptability [5]. (absolute number of feasible trajectories).



(a) Airspace with two aircraft and a weather cell

(b) Time space diagram for the airspace

Figure A.12: SSD with RTA and conflict constraints [5].

Two aircraft in conflict and a weather cell (congestion) is shown in Figure A.12(a). The controller has to re-route aircraft A along, a weather cell and has to avoid the conflict from aircraft B. They can choose two trajectories, A and B respectively. The distance between aircraft A and the weather cell is d_2. d_3 & d_4 are the distance from aircraft A and conflict with aircraft B. Aircraft A has to adhere to required time of arrival (RTA) within the airspace, irrespective of which trajectory the controller chooses. Time space diagram of this scenario is shown in Figure A.12(b). Trajectory B is infeasible because aircraft A is either in conflict with aircraft B or it is unable to adhere to both the RTA's. Whereas trajectory A remains feasible by conforming to both RTA's and also preserving/maintaining separation. The feasibility of any trajectory depends on the location of RTA's and conflict region. If there are no feasible solutions available then the airspace is said to be over-constrained and therefore some constraints have to be relaxed [5]. The decision of choosing a robust solution or a adaptable solution is controller dependent. This bias depends on the risk taking attitude of the decision maker. A more conserved controller may favor to choose a robust solution to minimize disturbance. Whereas an ambitious controller may endure with the disturbance so long a reasonable amount of adaptability remains in the airspace sector. Robustness can be defined by a simple equation,

$$RBT(t) = \sum_{i=1}^{f} P_i(t) = \frac{N_f(t)}{N(t)} \tag{A.2}$$

where, $RBT(t)$ is given robustness, $N_f(t)$ is number of feasible trajectories and $N(t)$ is total number of feasible trajectories (without disturbance).

A.5 Deal Utility

In all of the above experiments, conflict resolution was provided with only single aircraft capability. Which means only one aircraft involved in the conflict had to deviate from its original trajectory. Which meant one aircraft had to take the entire burden of flying more distance and burning more fuel (inefficient). There are research currently underway in which, the penalty is split and shared between all the parties involved in the conflict. Summation of penalty for multi-aircraft conflict resolution might be less when compared to the penalty suffered by only one aircraft in single-aircraft conflict resolution case. Current hub and spoke principle used by airlines will not be sufficient to handle the growth in air travel [6]. An agent is a "piece of code" in a program which analyzes the environment using all the inputs to make decisions, from which actions can be derived. Several agents combined together forms a multi-agent system [6]. Where agents can communicate, collaborate and compete among each other to accomplish goals. Automated negotiation protocols are used to resolve conflicts that is acceptable among all the parties involved in the conflict. Wollkind et al., in their research have assumed each aircraft in the airspace as an agent and a multi-agent system, each having their own goals i.e., destination, time frame of arrival, service standards etc. It is suggested that an on-board computer would run this program code simultaneously monitoring for any conflicts. If a conflict is detected the aircraft (agents) will be free to communicate with each other and negotiate a safe and efficient solution to resolve the conflict using a "Monotonic Concession Protocol". When a resolution is chosen, pilots will be alerted about the course/trajectory revision. This entire negotiation procedure would be executed automatically between agents without the participation of pilots [6].

Zlotkin and Rosenschein developed the monotonic concession protocol (MCP) in which all the agents involved in the negotiation uses a incremental bargaining process. Using this MCP approach, Wollkind et al., have devised a deal utility equation in which the parties involved in the conflict will together decide a solution to resolve the conflict. If in case, there are no solutions acceptable to either of the aircraft (parties) involved, the previous deal which was marginal close to acceptance by any one of the aircraft will be selected and implemented by the pilot [6]. Decision of selecting the previous deal is made based on the utility value of various deals which were considered. "A compromise is made between amount of utility lost by accepting the offer of the other agent to the amount of utility lost due to conflict [6]". The equation for risk utility is shown below, it is similar for other agent (considered as B in this paper [6]). If $Risk_A > Risk_B$ then agent B should accept the deal suggested by agent A.

$$Risk_A = \frac{Deal\ Utility_A(D_A) - Deal\ Utility_A(D_B)}{Deal\ Utility_A(D_A) - Deal\ Utility_A(D_{Conflict})} \tag{A.3}$$

When a conflict is eminent the agent uses a predetermined process which generates six alternate trajectories to choose from which are, left, right, up, down, speed up and slow down [6]. Aircraft flying within a sector has to adhere to strict time constraints. The predicted time from the beginning and end of the conflict dictates the generation of left-right turn trajectory. Agent knows the end location at the time when the protected zone overlaps. At which point two temporary way-points are generated at right angles to the heading. A three nautical mile buffer is assumed on either side of the aircraft laterally (right and left) at start and end points of the conflict. Similarly two more points are generated at the start and end of the conflict. A fifth temporary point is created several minutes after the conflict is predicted to end. This fifth point will be on the original trajectory which the agent will choose in order to return to its intended path after conflict resolution. Therefore creating two new trajectories comprising of five points, two on the left, two on the right and a rejoining point. If the agent decides to choose the left alternative, it would require an immediate left turn towards the first way-point, then to the second left way-point and then re-joining the original path at the rejoining point. Similarly on the right side. This can be visualized from Figure A.13,

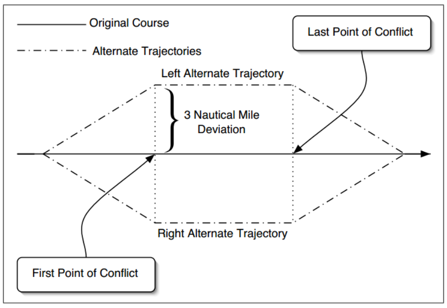


Figure A.13: Visualization of left and right trajectory for conflict resolution, (adapted from Wollkind et al.,) [6].

While our airspace becomes crowded inclusion of technologies like Free Flight become more significant. In order to resolve the aircraft conflicts, Free Flight will require a competent system that is critical and do not escalate the workload of a controller. The proposed system by Wollkind et al., was experimented to determine both safety and efficiency. It also proved that when cost functions are included while determining preferences, the final resolution achieved together by everyone had a higher utility than those provided by non cooperative methods [6]. Cooperative negotiations technique will allow multiple aircrafts (agents) attain a conflict resolution which is efficient and with minimized/reduced interaction with ground control.

A.6 Cooperative Management

The research regarding Cooperative Air Traffic Management (CO-ATM) was started by NASA Ames Research Center in order to accommodate and transform the capabilities of aircraft and Air Traffic Management (ATM) aligning within the goals of Next Generation Air Transportation System (NGATS) [22]. The main goal is to provide a framework to expand flexibility of operation for airspace users, efficiently and yet preserving safety.

Upgrading the information exchange between air-ground, distribution and modification in roles and responsibilities will significantly increase capacity and efficiency benefits. Distributed Air/Ground Traffic Management (DAG-TM) research identified critical areas such as safety, coordination, automation and mixed equipage concerns. This shift in roles and responsibilities will have to be steady from the current system to the next generation. And the aircraft operator who equip needs to be appreciated by certain incentives such as gain in efficiency (fuel burn, less flying time, priority in runway clearance etc) [22, 23].

CO-ATM predicts both sector and area controllers working side by side. Former controlling conventional aircraft and latter coordinating strategic trajectory revisions to flight crews with equipped aircraft, both in the same airspace connected via data link. Extended support will be provided to area controllers using automation tools, like hand offs, transfer of communication, and flight crews of aircraft which are properly equipped can be cleared to operate with increased autonomy and separation criteria can be delegated. In an experiment which calculated the spacing accuracy, it was found that aircraft-aircraft separation was maintained with the aid of air tools [22]. Cooperation between traffic management, controllers and flight crews is pivotal/crucial for handling the increased traffic demand.

Voice is the primary mode of communication between flight crews and controller in the current system. In order to reap the benefits of a co-operative system, aircraft needs to be equipped with data links, so that infrequent trajectory revisions and spacing clearance can be broadcast via data links. In order to enable fully integrated co-operative air/ground operations, aircraft and ground controller together need to equip themselves with technologies such as decision support tools for scheduling and trajectory revision, Flight Management System (FMS), data link communication between ground-based decision support tools and FMS, ADS-B, Airborne Separation Assurance System (ASAS) and Cockpit Display of Traffic Information (CDTI) on the flight deck. It will be outrageous to assume everyone will equip the above mentioned technology at the same time. Therefore the use of automation cannot be shifted overnight. Hence, gradually phasing out the old systems with new and improved systems is envisioned, without causing any delays to standard operations.

The current airspace capacity can be increased 2-3 folds by properly relegating and distributing the responsibility for separation of aircraft among multiple operators [22]. Any changes in trajectory is handled by area controller unless it is authorized by automation tools. Prevot et al., in their research on co-operative technologies found that, flight path predictability can be improved if sector controllers use FMS compatible procedures. Area controllers with the help of ground systems can check the requested trajectory change from flight crew, check for conflicts and traffic flow compliance to determine if it is safe and then approve it. In case a conflict is detected which cannot be eliminated with any trajectory revisions, the area controller has several ways to instruct the flight crew. They can task the flight crew to maintain spacing, allow the sector-controller to handle the aircraft, or provide immediate voice instruction to remove the impending conflict [22]. In adopting this technology, flight crew will involve in little or no voice communication. And also radio frequency change will be considerably decreased. The aircrafts which equip these above mentioned technologies will endure the most benefit because, more time is available for the controller to assist the flight crew. If everything goes according to plan, in the next phase, the proposed prototype system will be tested by simple mock-ups of the above mentioned technologies in real life environment with real traffic flows. This first hand experience will present a "reality check" [22], and allows the users (pilot and controller) to check the feasibility while interacting in a real life operational environment [22, 23].

A.7 Previous research on 4D trajectory with TSR representation

Klomp et al., and his colleagues conducted a batch experiment to investigate the change in robustness (minimum and average robustness) for a two aircraft crossing scenario under varying geometry [7]. The airspace considered for this batch experiment was an en-route airspace. Both aircraft, observed (F_{obs}) and second aircraft (F_{int}) are flying at FL300, with $250kts$ indicated air speed (IAS) ($\approx$ M0.67 or $400kts$ ground speed, no wind consideration). The minimum horizontal separation standard was maintained at $5NM$ (nautical miles). The conflict angle for the scenario is varied from 20° to 160°, changing from almost parallel to almost head-on. The entire experiment run was divided into two main conditions, one condition in which the observed aircraft passes in front of second aircraft and in another condition where it passes behind the second aircraft. In order to measure the change in robustness, aircraft were made to pass on the edge of the no-go area, therefore the minimum separation boundary (Closest Point of Approach (CPA)) was varied from $5NM$,$6NM$ and $7NM$. To ensure a fair calculation of robustness, for all the experiment conditions, the time taken for CPA of aircraft before the conflict was set to 10 minutes. They continued along the original path for further 10 minutes after CPA. In this batch experiment, no intermediate way-points were created (edge of no-go area), instead the time of entry for the second aircraft was varied such that at CPA one aircraft passes (in-front or behind) the other according to the set separation standard. Crossing geometry used in this batch evaluation is shown in Figure A.14,

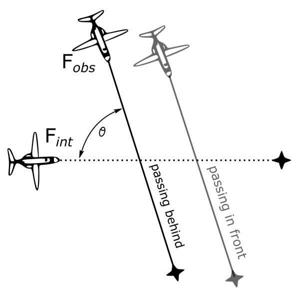
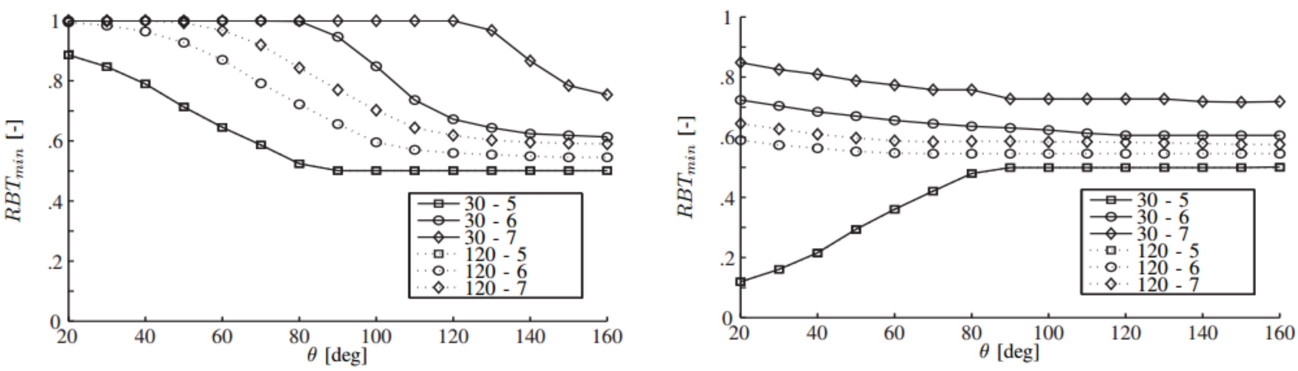


Figure A.14: Crossing geometry, adapted by Klomp et al., [7].

The parameters which were set constant while calculating robustness are, "the maximum heading disturbance (ϕ_{max}) = 80°, maximum speed disturbance (ΔV_{max}) = 20kts IAS (≈ M0.05 or 30kts ground speed). Range of heading was discretized in a step range of 5 and speed change in steps of 2.5kts IAS, from which a total 561 probe segments (n_i) per point was derived. Point based robustness was calculated every second along the trajectory. The look ahead time was also divided into two sets 1) Δt of 30 *seconds* (standard TCAS resolution Advisory) and 2) Δt of 120 *seconds* (standard ATC Short Term Conflict Alert time window)" [7].

The results from the batch analysis are explained below. In Figure A.15, Conflict angle (θ) in degrees is on the x-axis and value of robustness on the y-axis. The legends mention which line corresponds to CPA and look ahead time. The average robustness can be defined as the overall robustness divided by time within the airspace as the aircraft progress from entry to exit way-point in the airspace. Therefore if disturbance in the airspace is short lived, then the average robustness would be close to a value 1. Hence it is more important to notice the change in minimum robustness. It can be clearly seen from Figure A.15(a) and Figure A.15(b) that the value of minimum robustness for the observed aircraft is lower for the condition when it passes in front than for the passing behind maneuver (robustness value closer to 1 means better maneuver). Robustness calculated in this experiment was only for the aircraft whose trajectory was changed. The result proved that boundary seeking control actions (intermediate way-points at the edge of the no-go area in the TSR) will worsen the overall robustness. When the controller is informed about this impact on robustness for a particular set of control resolutions, controller will arrive at more efficient and safe solution preserving the trajectory robustness [7]. Minimum robustness was found to decrease as the conflict angle increased (till 90°) and for higher conflict angles the value settled and became constant. This trend can be noticed for all the different CPA and look ahead time conditions.

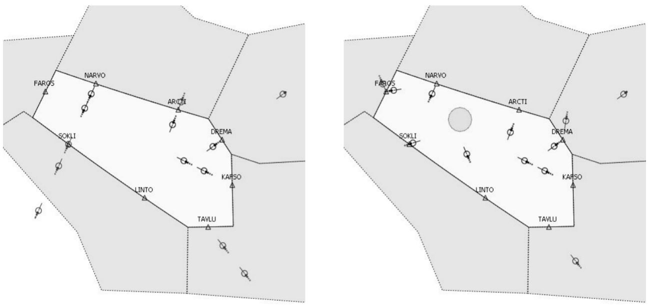


(a) Robustness$_{min}$ for passing behind

(b) Robustness$_{min}$ for passing in front

Figure A.15: Batch results, Minimum Robustness value for single-aircraft conflict resolution [7].

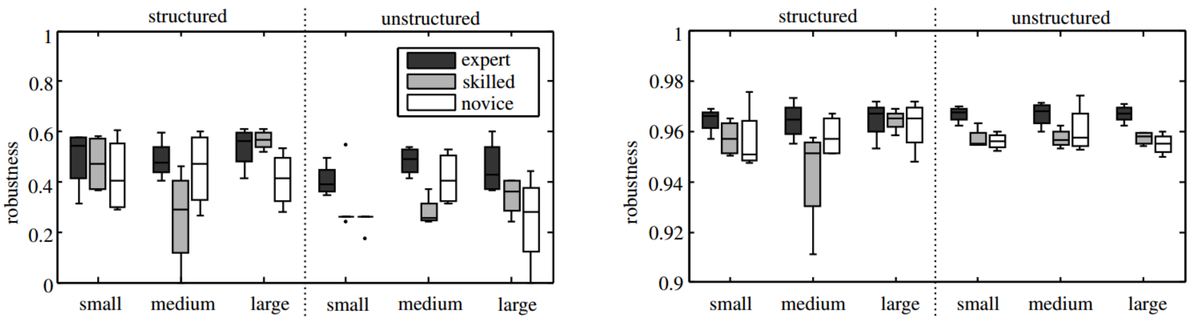
Klomp et al., in another experiment evaluated the affects of robustness for varying level of expertise of controllers. A HITL experiment was conducted where the participant were given a task to manage various scenarios of air traffic without the aid of any automated advisories (i.e., by using only the TSR alone) [8]. The group of participants were divided into three groups with increasing level of expertise. Goal of this experiment was 1) to examine the type of control strategies employed by the three groups when using TSR and 2) to determine if the control strategies differ under varying traffic and airspace design (low to high complexity). The traffic orderliness was varied from structured and unstructured, also airspace perturbations was also changed from small, medium and large perturbations. The participants had to manage traffic under six different traffic conditions, similar to as described in Table A.2. Each conditions were uniquely rotated, aircraft ID was changed and way-points renamed in order to eliminate control bias due to scenario recognition. Each condition consisted of 15 aircraft with eight entry/exit way-points and lasted 24 minutes in scenario time. The entire experiment was made to run at 4x normal speed, therefore in real time all the scenario lasted for about six minutes. More conflicts could be created by the participants themselves depending on the control actions chosen to eliminate the first conflict. Figure A.16 shows the difference in two scenarios,



(a) T_S-P_S condition (b) T_U-P_L condition

Figure A.16: Different traffic scenario/conditions, (adapted from Klomp et al.,) [8].

Results from this experiment showed that expert controllers employed more control actions. They applied small trajectory revisions more often and fine tuned their control action. This behavior was more pronounced for large perturbations in both structured and unstructured traffic condition. The minimum sector robustness change due to controller operations showed that expert controllers employ a more conservative approach while deciding a resolution. They often avoided choosing the actions which made the aircraft fly in narrow spaces. This was more evident in unstructured-large perturbation experiment condition, which suggested that, for more complex and unknown traffic pattern, they increased the spatial separation buffer [8].



(a) $RBT_{S_{min}}$ (b) $RBT_{S_{avg}}$

Figure A.17: Sector based Robustness for different traffic conditions, (adapted from Klomp et al.,) [8].

Number of added track miles was also calculated in this experiment. "Added track miles is the measure of total deviation in nautical miles from the original aircraft trajectory" [8]. Results showed that, added track miles was more pronounced for the expert group. Mainly because they preferred strategies which made the aircraft fly with more separation buffer, instead of flying close to the constrain boundaries which would result in reduced track miles. Overall, all the participants suggested that TSR provided a spontaneous and clear overview regarding all the available rerouting options for a selected aircraft. One remark which everyone pointed out was that, the non-availability of option to control the aircraft which was yet to enter the airspace sector, which could create new conflicts when it entered the sector.

Expert controllers were more conserved with their control actions which resulted in higher level of robustness, whereas students (novice) and domain experts with zero operational experience employed a reactive strategy and opted to fly in tighter control spaces. Expert controllers exhibited less trust towards TSR and hence were apprehensive in relegating more tighter solutions. Because, TSR used in this experiment did not include uncertainties in the displayed information into account. Options such as ‘passing behind’ control actions instead of ‘passing-in-front’ option are common ATC practice employed. In order to train novice controllers, these common practices should be made explicit, so that they choose more robust solutions. It was observed that robustness changes with the level of expertise of the participants. The interface used in the experiment was found to be effective for experience controllers, since they applied wise knowledge based decision without compromising safety and efficiency.

B

PRELIMINARY ANALYSIS

Based on the findings from the literature survey, a preliminary analysis was conducted for this thesis assignment. Using the results explained in the above sections, such as the best practices of ATCo etc., the traffic scenarios for the preliminary experiment are designed. Also the initial results from the analysis are explained.

B.1 Preliminary Analysis

The entire preliminary analysis traffic scenario were designed using a JAVA©based tool called the Travel Space Software. The airspace was designed using the "airspace designer tool", this step is **pre-processing**. Aircraft and way-points were added using the traffic builder tool. The airspace sector along with traffic was loaded and simulated using the "travel space software". Log files are created after each simulation run. These log files contain all the necessary data which is required to calculate the robustness, workload and number of added track miles (in nautical miles), this step is the **solution**. Using "log viewer" final results are calculated. Log viewer creates comma separated excel sheet, using the data from these excel sheets, respective robustness plots are created using MATLAB. This final step is **post-processing**. Multi-aircraft conflict resolution capability was available in this 4D trajectory interface with TSR, which is used in this thesis assignment and also for the preliminary analysis. Resolution provided was restricted to only 2D (lateral changes) and time constraints.

The objective of the preliminary analysis was to understand the change in robustness for varying conflict angles using a 4D trajectory interface with the TSR having a multi-aircraft conflict resolution capability. Results from the experiments conducted by Klomp et al., [7, 8] will be used as a baseline to check and compare the results for multi-aircraft conflict resolution. The airspace sector assumed for this preliminary analysis is a square shaped design spanning 100*100 nautical miles, shown in Figure B.3. Currently due to radar resolution constraints, airspace sector size is restricted and depends on radar coverage. In the future with help of ADS-B data link, aircraft intent can be broadcast to all the concerned parties using which, conflict detection can be relegated to the flight crew. Thereby sector size can be considerably bigger than the airspace sector size in current operations. This is the rationale for choosing a sector of 100*100nm for this preliminary analysis. Therefore using the findings from the literature, the preliminary analysis was divided into two main sections (experiment conditions), 1) No Speed Bias and 2) Speed Bias. This experiment was restricted to only one aircraft type i.e Airbus A320, in order to keep the number of outcomes (results) to a minimum. At a time there were only two aircraft in the airspace sector. For all the traffic conditions, first the robustness was calculated using single-aircraft conflict resolution capability and later using multi-aircraft conflict resolution capability. Number of added track miles was measured and compared for both the cases. Aim here was to find evidence to prove multi-aircraft resolution is indeed better than single-aircraft resolution.

1. No speed-bias: In this scenario, both aircraft traveled at same speed i.e Groundspeed = 403 ≈ 0.68 mach.

2. Speed Bias: In this scenario one of the two aircraft traveled faster than the other i.e Groundspeed = 458 ≈ 0.75 mach.

These two scenario were further divided into different conflict angles, based on the experiment from Klomp et al., [8, 10] (from almost parallel to almost head on). Also based on International Civil Aviation Organization 1996, robustness was measured for the following conflict angles. An illustration of different experiment conditions considered for this preliminary analysis is shown in Figure B.1.

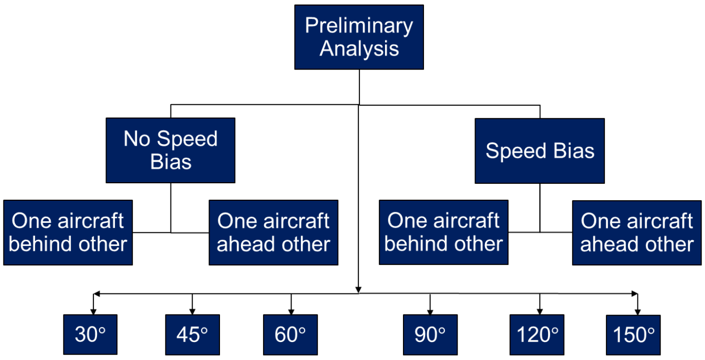


Figure B.1: Experiment Condition considered for preliminary analysis.

Multi-aircraft conflict resolution will not be beneficial for 180° conflict angle because the TSR for both the aircraft will have the same possibilities of "go & no-go areas", in order to eliminate the conflict either one of the aircraft has to change its trajectory. Therefore analysis was fixed to the above mentioned six conflict angles. The initial design of the airspace sector used in this preliminary analysis is shown in Figure B.3.

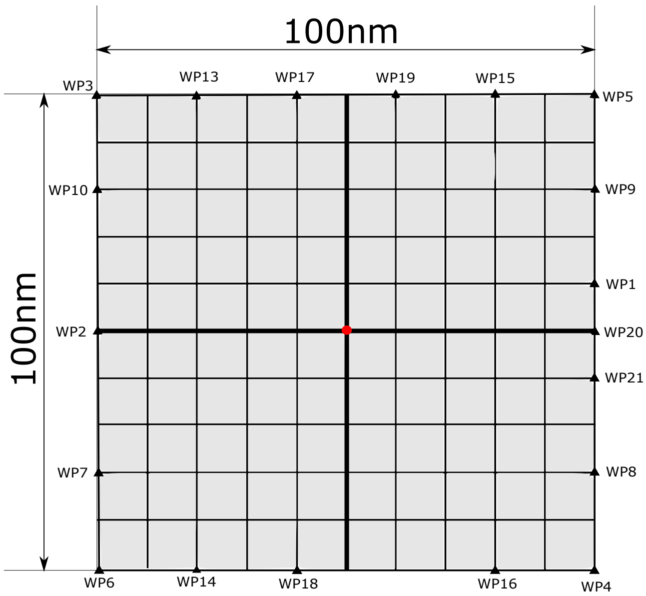


Figure B.2: Initial Airspace sector design with sector entry/exit way-points.

B.2 Analysis of Conflict Resolution

As discussed in the literature chapter, the best practices from ATC depend on the expertise of controller [8]. Kirwan et al., [10, 13] in their findings have extensively described the logic behind every control action and the reason for choosing one over the other, based on these findings following two control actions are defined: (note: RAD1 and RAD2 are the aircraft ID assumed in this preliminary analysis)

1. One aircraft (RAD1) behind second aircraft (RAD2) (Passing behind)
2. One aircraft (RAD1) ahead second aircraft (RAD2) (Passing front)

The above mentioned control actions were first resolved using single-aircraft conflict resolution and then using multi-aircraft conflict resolution. The robustness value measure in this thesis assignment is the combined robustness value for both the aircraft involved in the conflict, whereas in the experiments conducted by Klomp et al., the robustness measured was for the individual aircraft (specific aircraft considered). Figure B.3 describes how a conflict angle is defined for this preliminary analysis.

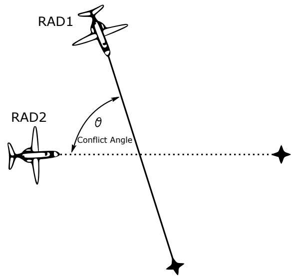
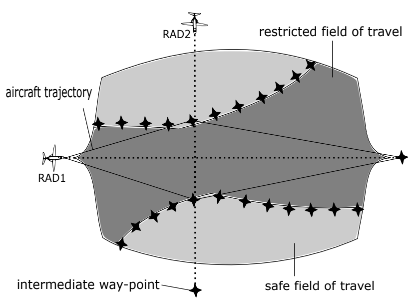


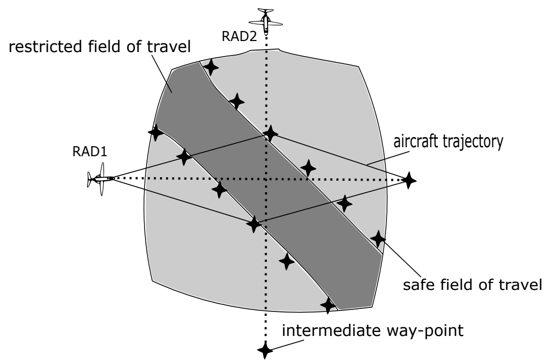
Figure B.3: Definition of conflict angle.

B.3 Calculation of Robustness for different conflict angles

In this section the flexibility (robustness) value calculated for different conflict angles are explained. Intermediate way-points were positioned at the edge of the separation standard of $7nm$ (nautical miles) (Note: $2.5nm$ separation on each aircraft, plus $2nm$ of additional separation was included in the interface) and at the start of go-area (safe field of travel). As the TSR provides all the solution of safe field of travel, way-points were placed randomly along the stretch of the go-area from one end to other (entry to exit point of aircraft). Depending on the length of the TSR each conflict angle scenario was further divided into individual way-point scenario (different way-points along the edge of separation minimum). This can be visualized from the TSR representation for a 90° conflict angle shown in Figure B.4.



(a) SACR



(b) MACR

Figure B.4: Travel Space Representation for 90° conflict angle with intermediate way-points marked.

As shown in Figure B.4 for each scenario, intermediate way-points were placed on the edge of the restricted area of travel ($7nm$ separation minimum). Depending on the size and shape of the TSR, for each conflict angle scenario the change in robustness value was calculated for every intermediate way-point location. (Note: Above figure shows the entire simulation run for 90° conflict angle. Only one intermediate way-point was placed at a time in each simulation run. Robustness and number of added track miles were calculated for every individual way-point simulation run).

B.4 Metric Set-up

In order to keep the results comparable to the results from the batch study conducted by Klomp et al., a similar metric as used in the batch study to calculate the robustness value was considered for this preliminary analysis:

1. Look forward time is set to 120 seconds
2. Maximum heading difference is set to 80°
3. The maximum speed disturbance is set to 20kts IAS (ΔV_{max})
4. Heading angle was discretized with 5 degrees
5. Speed range in interval of 10kts IAS

In the next section the robustness plot for all the conflict angle scenarios will be shown.

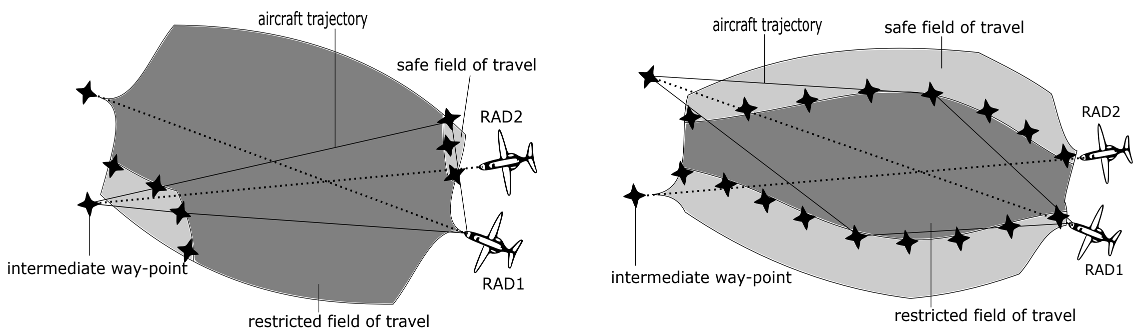
B.5 TSR and Robustness Plots for different conflict angles - No Speed Bias

In this section the TSR and robustness plot for all the conflict angles will be shown. Preliminary experiment was conducted to check if the robustness value was dependent on airspace design and conflict angle. For every simulation run, intermediate way-point was shifted on the edge of 7nm separation. This was done in order to observe the change in the minimum robustness value with respect to the shift in the intermediate way-point.

B.5.1 30° conflict angle

In this section the robustness plot for 30° conflict angle will be discussed. 30° conflict angle was calculated based on Figure B.3 with the help of trigonometric equations. The TSR for both SACR and MACR are shown in Figure B.5.

Robustness plot from all the simulation runs will be discussed in the coming section. "Rad1 and Rad2" are the aircraft ID's considered. All the important terms such as safe field of travel, restricted area of travel, aircraft trajectory and intermediate way-point are marked in the Figure B.5.



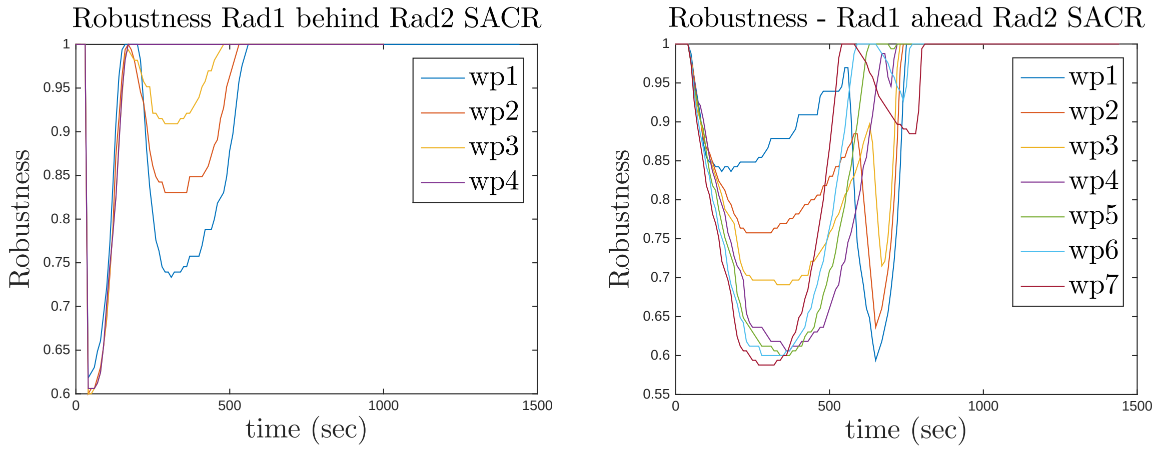
(a) SACR (b) MACR

Figure B.5: Travel Space Representation for 30° conflict angle with intermediate way-points marked.

We can clearly notice from the above figures that, MACR (Figure B.5(b)) provides the controller with more options to place a new intermediate-way-point when compared to SACR (Figure B.5(a)).

Robustness plot for 30° conflict angle, for all the simulation runs (different way-point scenario) is shown in

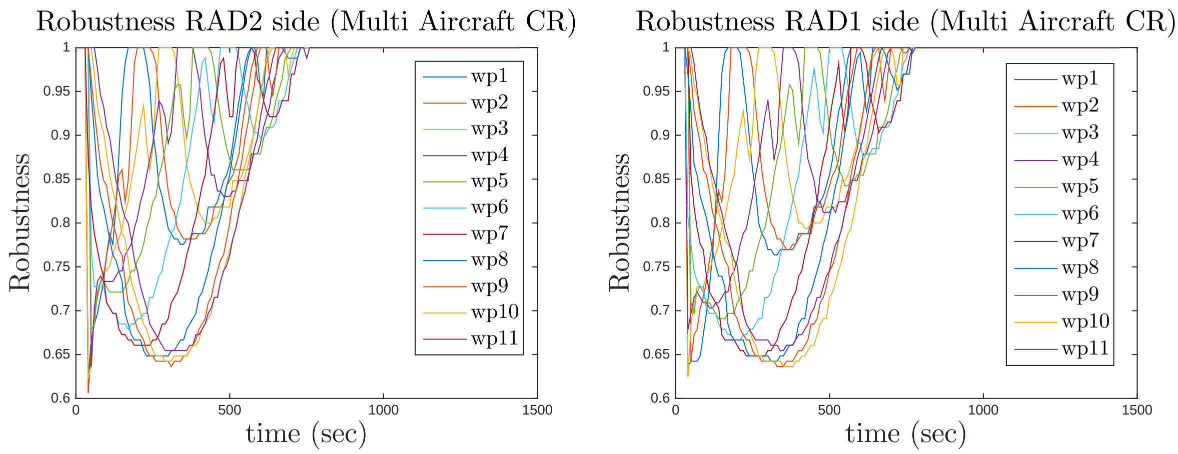
Figure B.6. (Note: Since we want to check the change in minimum robustness, only minimum robustness plot is shown below. Also Rad2 side means Rad1 behind Rad2 and Rad1 side means Rad1 ahead Rad2).



(a) RBT$_{min}$ - Rad1 behind Rad2

(b) RBT$_{min}$ - Rad1 ahead Rad2

Figure B.6: RBT$_{min}$ for 30° conflict angle with single-aircraft conflict resolution.



(a) RBT$_{min}$ - Rad1 behind Rad2

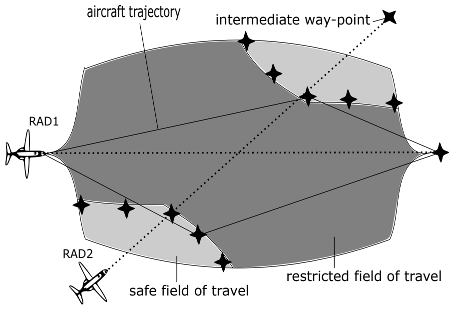
(b) RBT$_{min}$ - Rad1 ahead Rad2

Figure B.7: RBT$_{min}$ for 30° conflict angle with multi-aircraft conflict resolution.

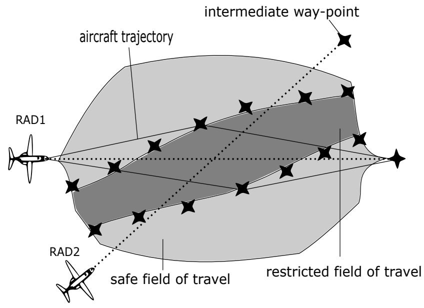
It can be seen from Figure B.6 and Figure B.7 that, shape of the plot remains same but it shifts in time (x-axis). For the passing in front maneuver, robustness plot is spread out which basically means, after resolving the conflict the controller has to constantly monitor the progress. Even though this maneuver maintains more airspace robustness, increase in monitoring time can make the controller omit this type of control action. Also it can be noticed from Figure B.7 that both the plots look similar (SACR & MACR), Figure B.7(b) is more robust than Figure B.7(a). The same trend can be noticed for all the conflict angles. Therefore from the next scenario onwards only one of the subplots will be shown. The other subplot for multi-aircraft conflict resolution will be shown in the appendix C (Additional Results - PA) of this report.

B.5.2 45° conflict angle

Similar to the above section, TSR and $Robustness_{min}$ plot for 45° conflict angle are as follows. (Note: In the title shown in the plots, single means single aircraft conflict resolution and multi means multi-aircraft conflict resolution).

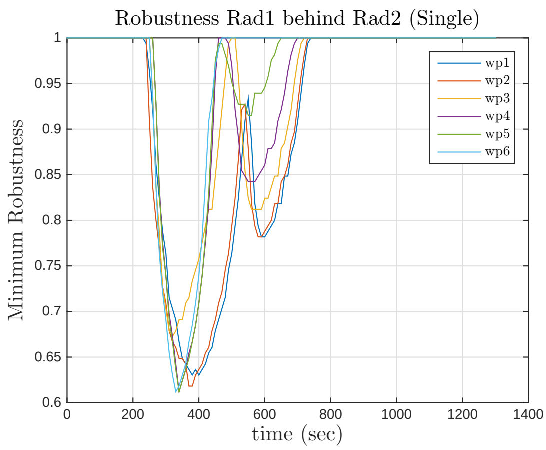


(a) SACR

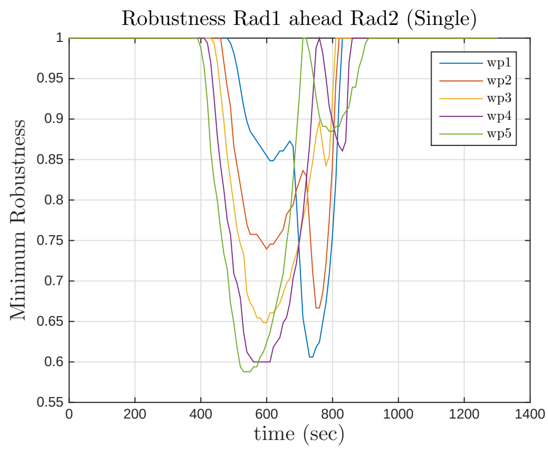


(b) MACR

Figure B.8: Travel Space Representation for 45° conflict angle with intermediate way-points marked.

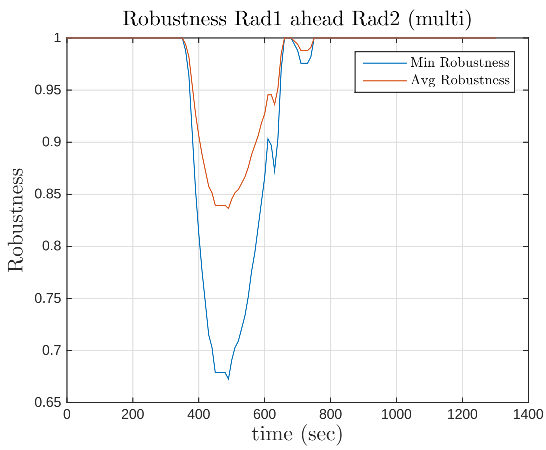


(a) RBT$_{min}$ - Rad1 behind Rad2

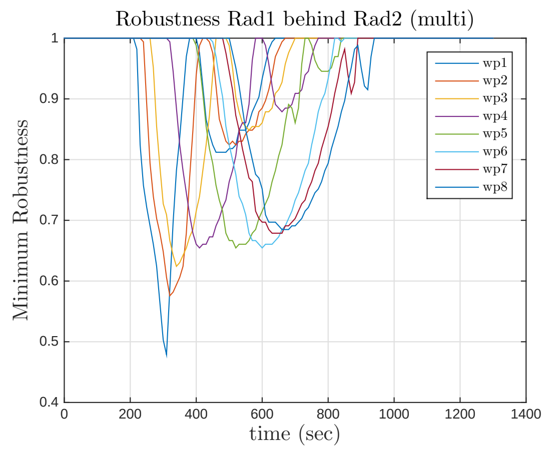


(b) RBT$_{min}$ - Rad1 ahead Rad2

Figure B.9: RBT$_{min}$ for 45° conflict angle with single-aircraft conflict resolution.



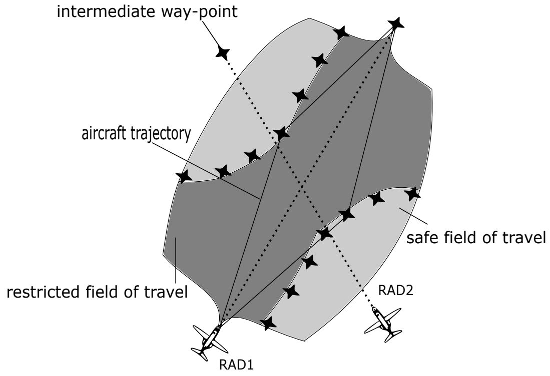
(a) RBT$_{min}$ & RBT$_{avg}$ - Rad1 ahead Rad2 way-point 4 scenario



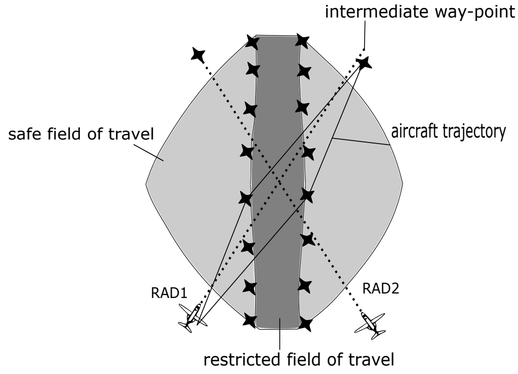
(b) RBT$_{min}$ - Rad1 behind Rad2 all intermediate way-point scenario

Figure B.10: Robustness for 45° conflict angle with multi-aircraft conflict resolution.

B.5.3 60° conflict angle

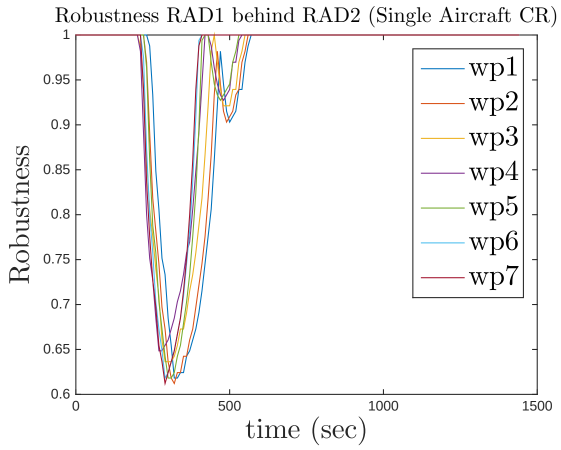


(a) SACR

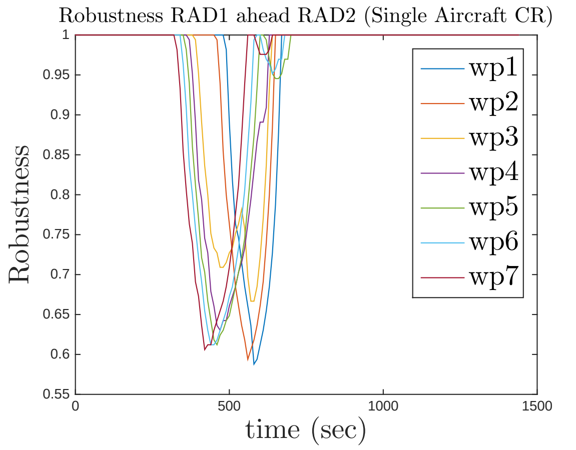


(b) MACR

Figure B.11: Travel Space Representation for 60° conflict angle with intermediate way-points marked.



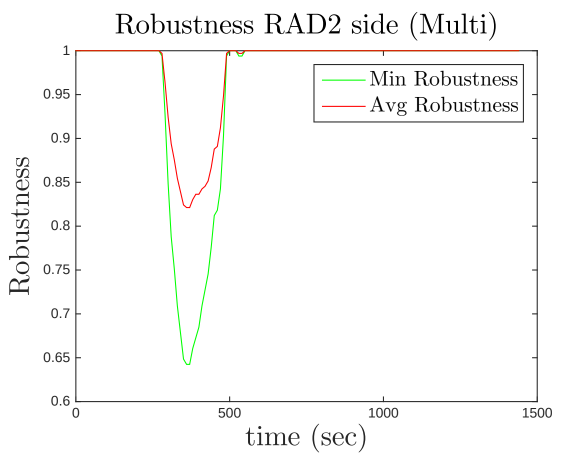
(a) RBT$_{min}$ - Rad1 behind Rad2



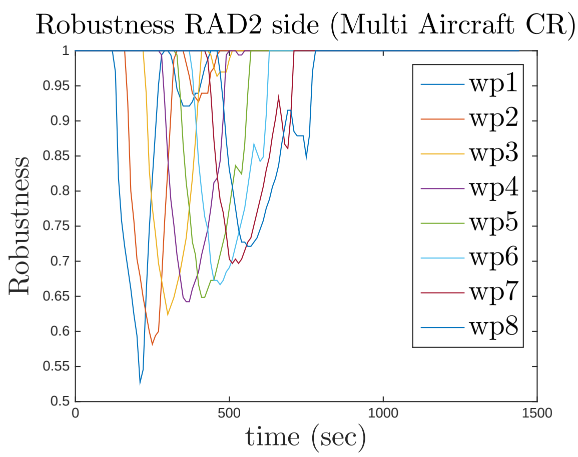
(b) RBT$_{min}$ - Rad1 ahead Rad2

Figure B.12: RBT$_{min}$ for 60° conflict angle with single-aircraft conflict resolution.

(Note: Rad2 side means Rad1 behind Rad2)



(a) RBT$_{min}$ & RBT$_{avg}$ - Rad1 behind Rad2 way-point 4 scenario

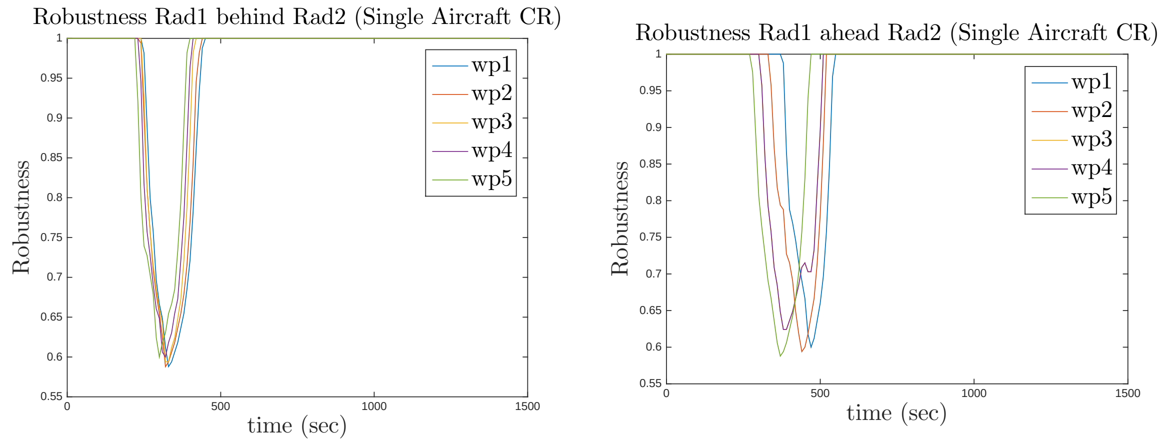


(b) RBT$_{min}$ - Rad1 behind Rad2 all intermediate way-point scenario

Figure B.13: Robustness for 60° conflict angle with multi-aircraft conflict resolution.

B.5.4 90° conflict angle

The TSR for 90° conflict angle is shown in Figure B.4. Therefore only the robustness plots will be shown in this section.

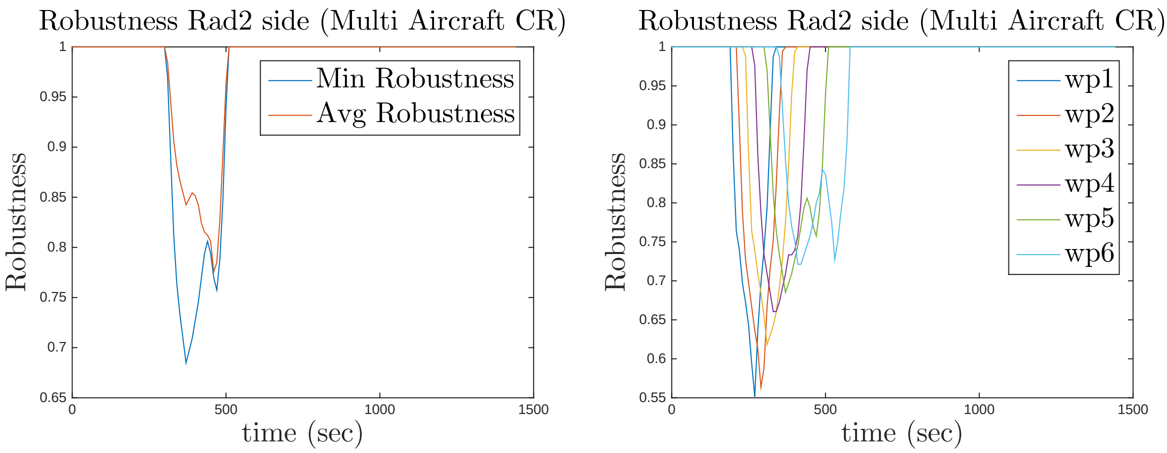


(a) RBT$_{min}$ - Rad1 behind Rad2

(b) RBT$_{min}$ - Rad1 ahead Rad2

Figure B.14: RBT$_{min}$ for 90° conflict angle with single-aircraft conflict resolution.

(Note: Rad2 side means Rad1 behind Rad2)

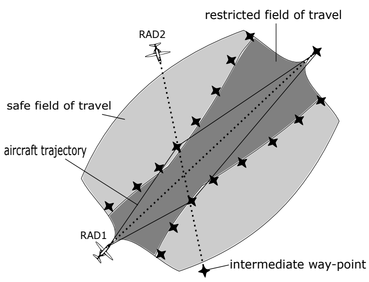


(a) RBT$_{min}$ & RBT$_{avg}$ - Rad1 behind Rad2 way-point 5 scenario

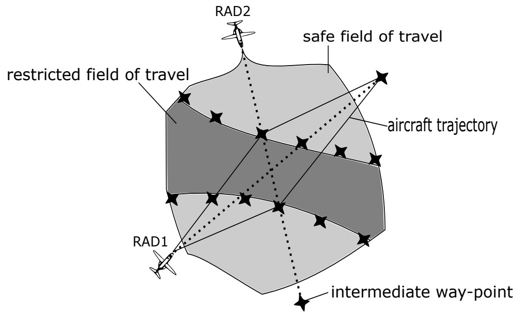
(b) RBT$_{min}$ - Rad1 behind Rad2 with multi-aircraft conflict resolution

Figure B.15: Robustness for 90° conflict angle with multi-aircraft conflict resolution.

B.5.5 120° conflict angle

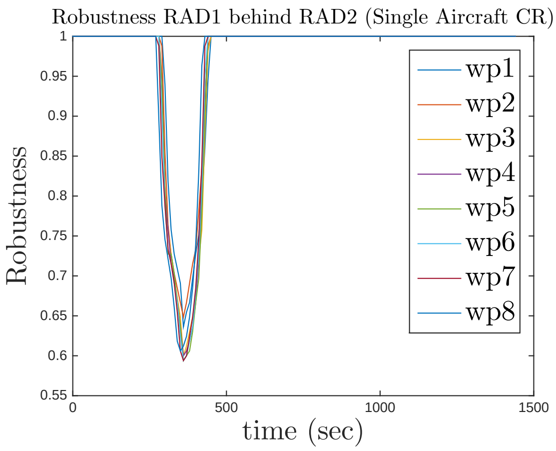


(a) SACR

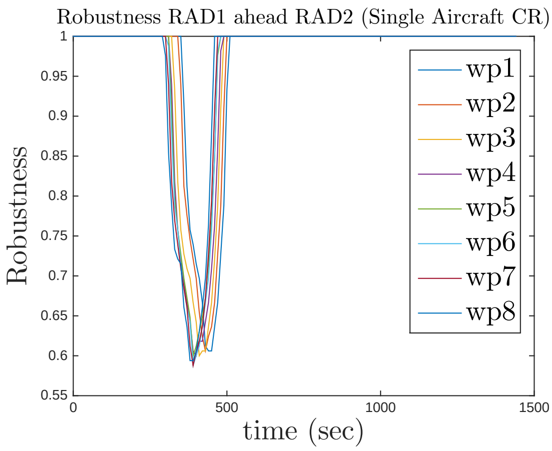


(b) MACR

Figure B.16: Travel Space Representation for 120° conflict angle with intermediate way-points marked.



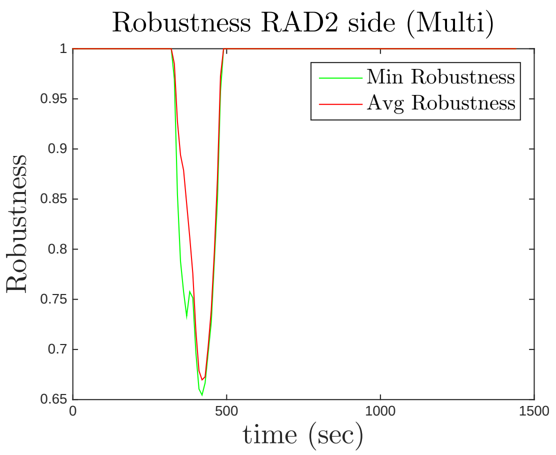
(a) RBT$_{min}$ - Rad1 behind Rad2



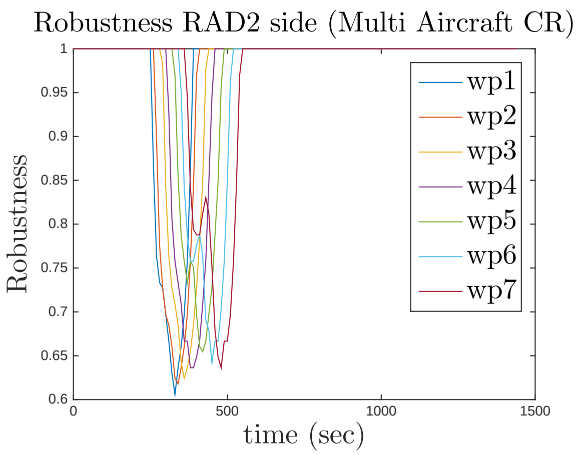
(b) RBT$_{min}$ - Rad1 ahead Rad2

Figure B.17: RBT$_{min}$ for 120° conflict angle with single-aircraft conflict resolution.

(Note: Rad2 side means Rad1 behind Rad2)



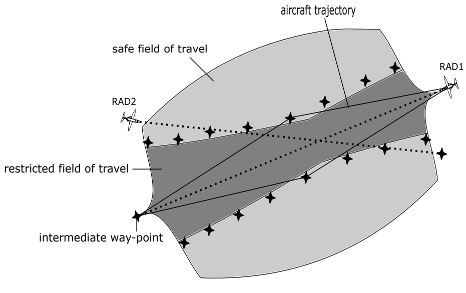
(a) RBT$_{min}$ & RBT$_{avg}$ - Rad1 behind Rad2 way-point 5 scenario



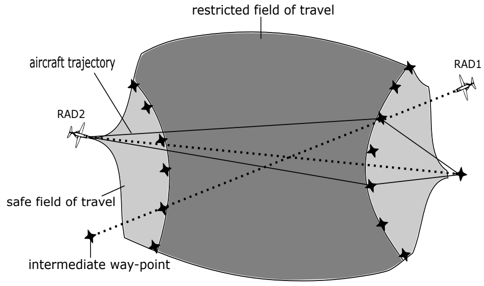
(b) RBT$_{min}$ - Rad1 behind Rad2 all intermediate way-point scenario

Figure B.18: Robustness for 150° conflict angle with multi-aircraft conflict resolution.

B.5.6 150° conflict angle

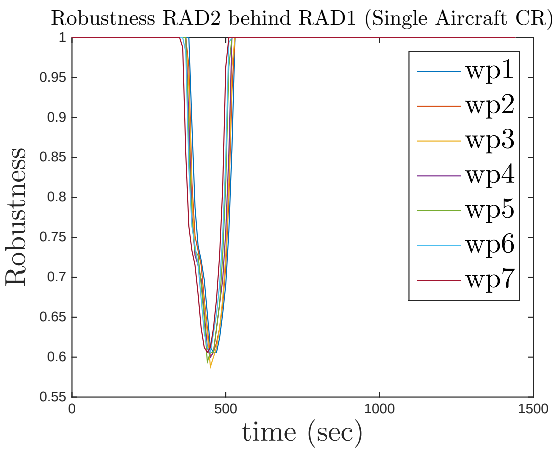


(a) SACR

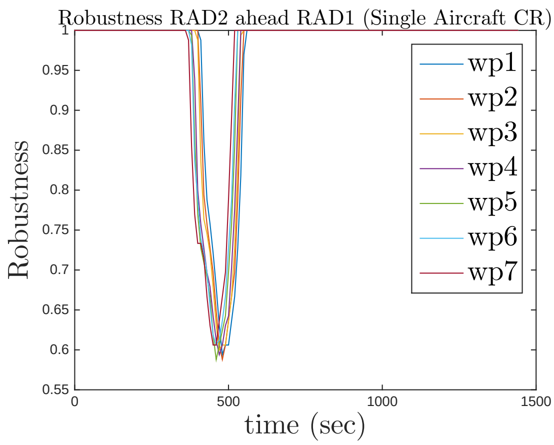


(b) MACR

Figure B.19: Travel Space Representation for 150° conflict angle with intermediate way-points marked.



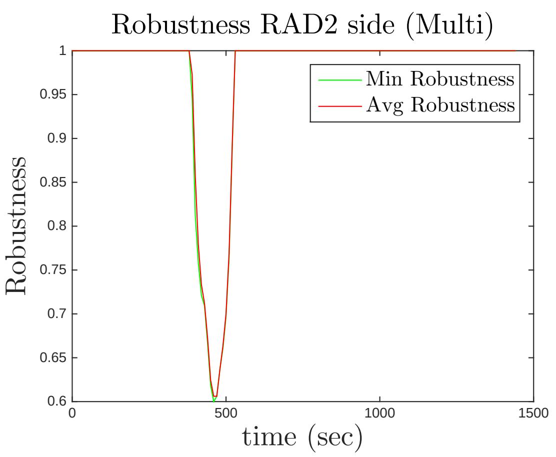
(a) RBT$_{min}$ - Rad2 behind Rad1



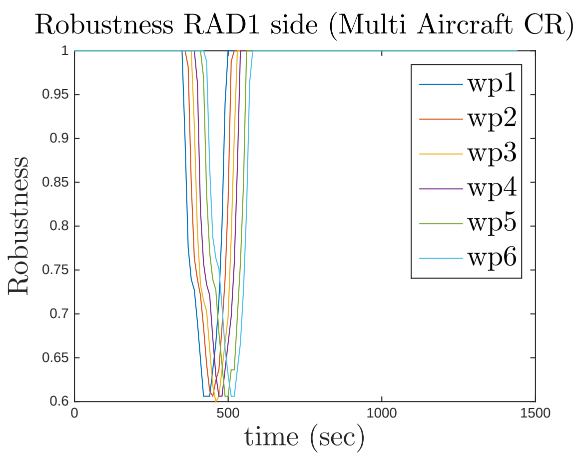
(b) RBT$_{min}$ - Rad2 ahead Rad1

Figure B.20: RBT$_{min}$ for 150° conflict angle with single-aircraft conflict resolution.

(Note: Rad2 side means Rad2 behind Rad1)



(a) RBT$_{min}$ & RBT$_{avg}$ - Rad2 ahead Rad1 way-point 4 scenario

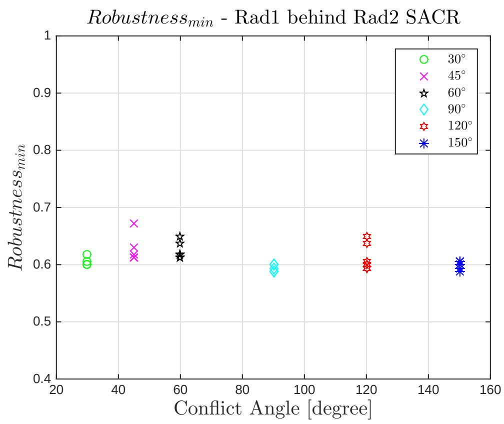


(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate wp scenario

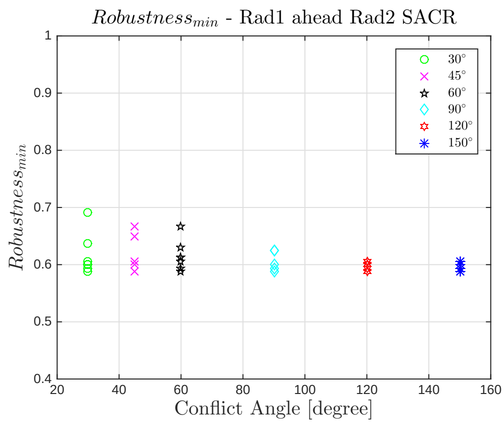
Figure B.21: Robustness for 150° conflict angle with multi-aircraft conflict resolution.

B.6 Discussion of results

The results from all the scenarios with different conflict angles are discussed in this section. Every conflict angle was further divided into several intermediate way-point simulation runs which depended on the number of intermediate way-points which were used in the simulation. This can be clearly visualized from TSR representation for each conflict angles shown in the above sections. $RBTmin$ value was calculated for each simulation run (intermediate way-points scenarios). This can be visualized by the plots which will be shown below. As explained earlier, airspace is said to be more robust if its robustness value is closer to 1. First let us have a look at robustness plot for SACR and then for MACR.



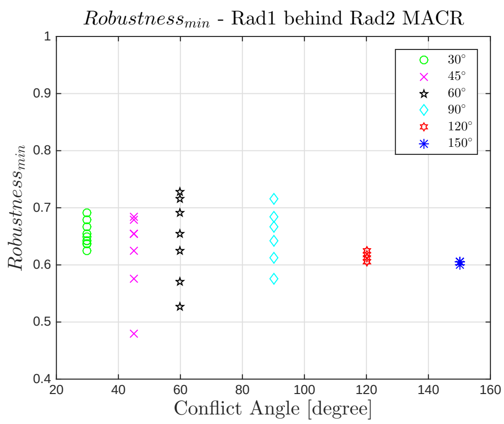
(a) RBT$_{min}$ - Rad1 behind Rad2 scenario



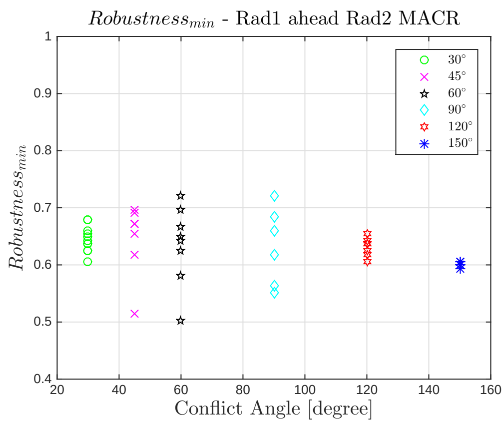
(b) RBT$_{min}$ - Rad1 ahead Rad2 scenario

Figure B.22: RBT$_{min}$ for all the scenario with Single-aircraft conflict resolution (SACR) capability.

The rbustness value for acute angle conflicts (0° - 90°) is more than 0.6 for going behind scenario. We can see the TSR shown in Figure B.5 for 30° conflict angle, there are more options available for the controller with respect to control actions (safe area of travel) using MACR (Figure B.5(b)) as compared to SACR (Figure B.5(a)). Same trend can be observed for all the other conflict angle scenarios. For higher conflict angles (almost head on) robustness value does not fluctuate and settles down to a value of < 0.6. For going ahead scenarios, robustness value is better for lower conflict angles (0.6-0.7). Robustness value for higher conflict angles are similar for both the maneuvers.



(a) RBT$_{min}$ - Rad1 behind Rad2 scenario



(b) RBT$_{min}$ - Rad1 ahead Rad2 scenario

Figure B.23: RBT$_{min}$ for all the scenario with multi-aircraft conflict resolution (MACR) capability.

Immediately we can see from the above plots that for lower conflict angles with multi-aircraft conflict resolution (MACR), robustness value is better (0.7 - 0.74) than single aircraft conflict resolution (0.59 - 0.69) for both maneuvers as shown in Figure B.23. It can also be observed from the above plots that in terms of preserving robustness value for higher conflict angles, MACR and SACR resulted in almost similar values. But for certain intermediate way-point locations the robustness value resulted in worse value for MACR (i.e 45° conflict angle - 0.48). For the same conflict angle, in the SACR case, the least robustness value is 0.61.

Therefore, robustness is either better than SACR or worse in some cases. After investigating it was found that, RBT$_{min}$ value depends on the position of placement of the intermediate way-point. After careful observations, position of these way-points were found. The way-point position which resulted in a worse value of robustness are marked as red way-point in Figure B.24. In order to maintain high airspace robustness, placement of new way-points needs to be avoided in these marked positions. Therefore, the end values of robustness depends on the placement of new intermediate way-point on the TRS. It is difficult for novice controllers to know this fact. Hence participants need to undergo proper training before the main HITL experiment, so that control-actions can be further refined to preserve robustness. Overall MACR was better than SACR in terms of preserving robustness.

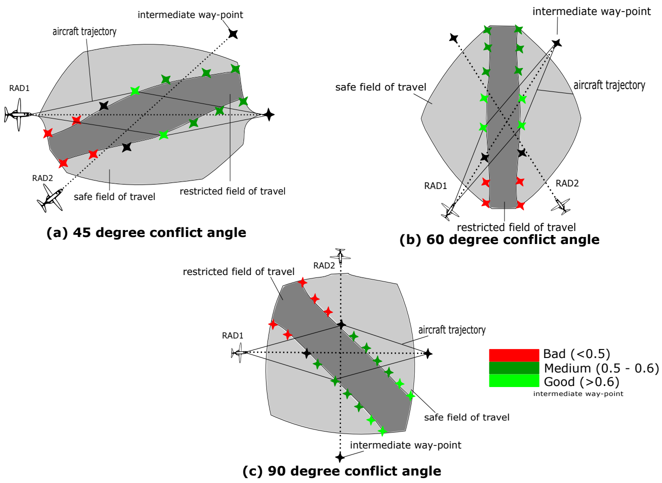


Figure B.24: Way-point position for low RBT$_{min}$ value.

B.6.1 Number of added track miles

Figure B.25 summarizes the average added track miles for all the different conflict angles for both single-aircraft and multi-aircraft resolution case. All the intermediate way-point simulation runs was averaged out for every conflict angle scenario resulting with one value of added track miles.

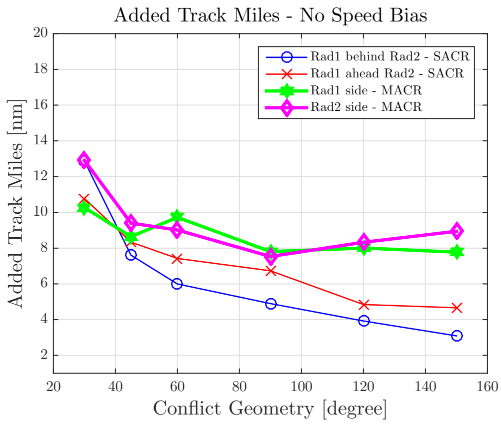


Figure B.25: Average track miles for all the conflict angle scenario.

As seen from the Figure B.25, only for 30° conflict angle case, extra added track miles flown (cumulative) in multi-aircraft case is less when compared to single-aircraft case. Whereas in all the other conflict angle cases, track-miles flown is more. Mainly because, in MACR case, both the aircraft has to deviate from their original trajectory, hence the track miles from both the aircraft are summed. Despite track miles flown being more for MACR, the minimum robustness value was better when compared to SACR.

One important parameter which needs to be addressed is, mental-model conformity of ATC controllers with the working of TSR used in this 4D trajectory interface. When using SACR capability, controllers can clearly observe the change in trajectory for the aircraft under consideration. One aircraft will either go behind or ahead the other depending on the resolution provided by the ATCo. Also they can clearly see and predict which aircraft arrives first at the intermediate way-point location. Whereas in MACR case, after providing a control action to the aircraft, both aircraft converge to a common new intermediate way-point (merge point). Even though one aircraft either goes behind or ahead of the other (i.e., depending on which side the new intermediate way-point is placed) initial motion of both aircraft can cause a disparity in minds of a controller. Although eventually conflict is eliminated, this mental-model mismatch (non-conformance) can decrease the favorability towards this new resolution capability. Hence proper training and explanation of the working of the interface could phase out this controller dislike towards multi-aircraft conflict resolution TSR interface.

B.7 Speed Bias

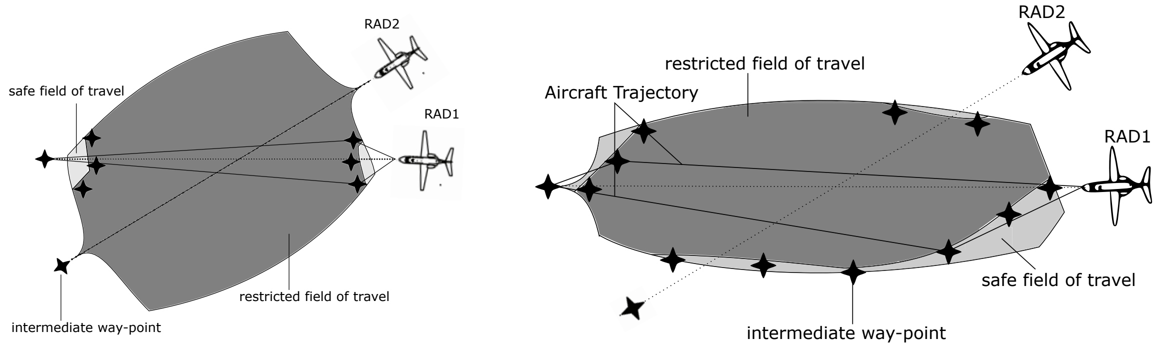
The conflict angles considered in this section were the same as used in the previous scenarios. One among the two aircraft was made to fly faster than the other. Faster aircraft traveled at ground speed (GS) of 462 or ≈ 0.78 mach. Whereas the slower aircraft at GS 403 and ≈ 0.68mach. Table B.1 provides a description of which aircraft was considered to be the slower aircraft:

Table B.1: Faster aircraft based on conflict angle scenario.

Conflict Angle	Slower Aircraft
30 degree	RAD2
45 degree	RAD1
60 degree	RAD2
90 degree	RAD2
120 degree	RAD2
150 degree	RAD2

B.7.1 30° conflict angle

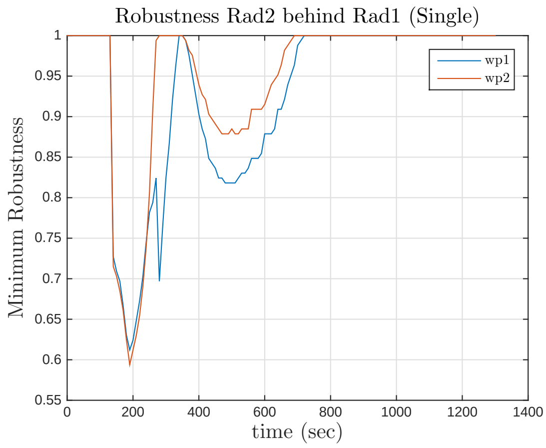
The change in robustness value was calculated in a similar way to "no speed-bias" scenario. TSR representation and robustness plots are shown below. Common ATC practice is to allow the slower aircraft to go behind the faster aircraft [10, 13].



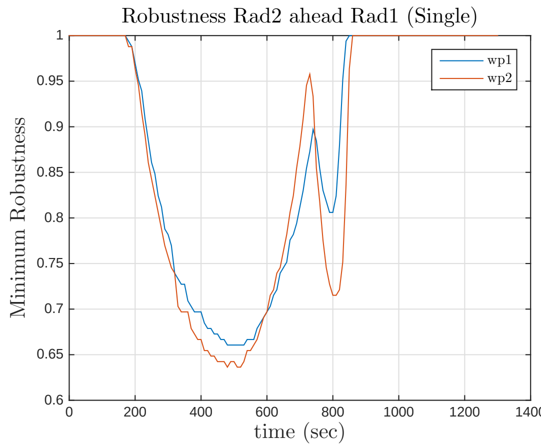
(a) SACR

(b) MACR

Figure B.26: Travel Space Representation for 30° conflict angle with intermediate way-points marked (Rad1 faster).



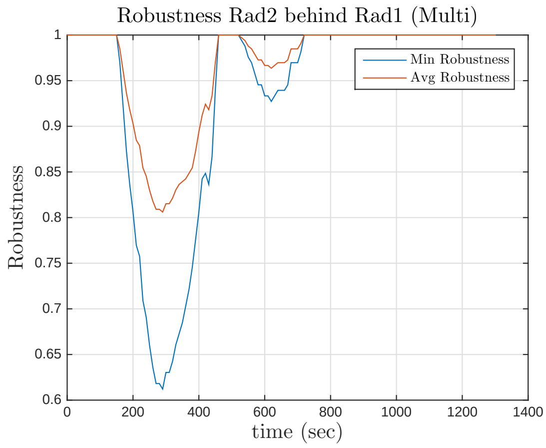
(a) RBT$_{min}$ - Rad2 behind Rad1



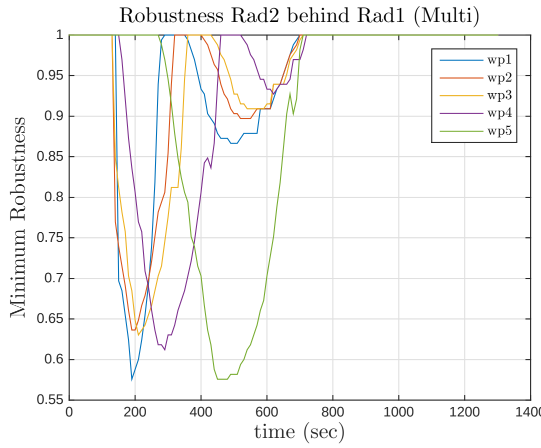
(b) RBT$_{min}$ - Rad2 ahead Rad1

Figure B.27: RBT$_{min}$ for 30° conflict angle with single-aircraft conflict resolution.

As we can see from Figure B.27, the least robustness value in Figure B.27(a) is 0.6 where as in Figure B.27(b) it is 0.64. Slower aircraft going ahead of the faster aircraft maintains airspace robustness better than the common ATC practice maneuver. Also we can notice from the robustness plot (Figure B.27(b)) that it is stretched with a value of 0.64 for longer period. Whereas in Figure B.27(a) it reaches a low value of 0.6 for a fraction and then robustness value continues to reach a value of 1. The value of 0.64 being extended in B.27(b) could increase the monitoring time required from ATCo. Therefore although mathematically this maneuver preserves the airspace robustness better, the controllers acceptance can vary due to the increased monitoring time until the conflict is resolved. Robustness plot for multi-aircraft conflict resolution is shown in Figure B.28. RBT$_{min}$ and Robustness$_{average}$ plot for one of the way-point case is shown in Figure B.28(a).



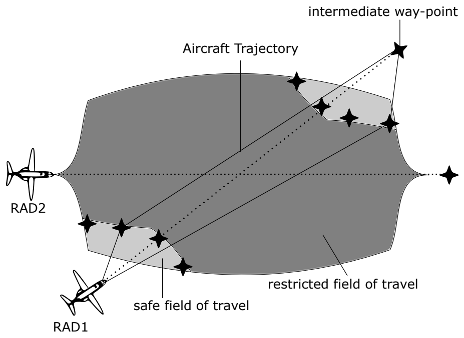
(a) RBT$_{min}$ & RBT$_{avg}$ - Rad2 behind Rad1 for scenario way-point 1



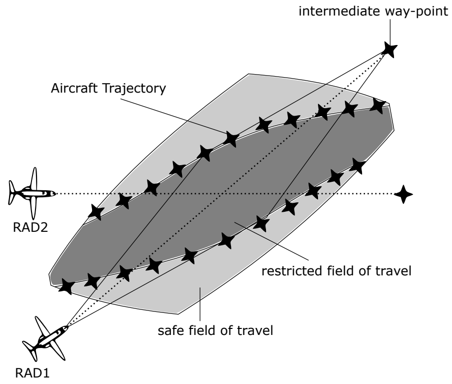
(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate way-point scenario

Figure B.28: Robustness for 30° conflict angle with multi-aircraft conflict resolution.

B.7.2 45° conflict angle

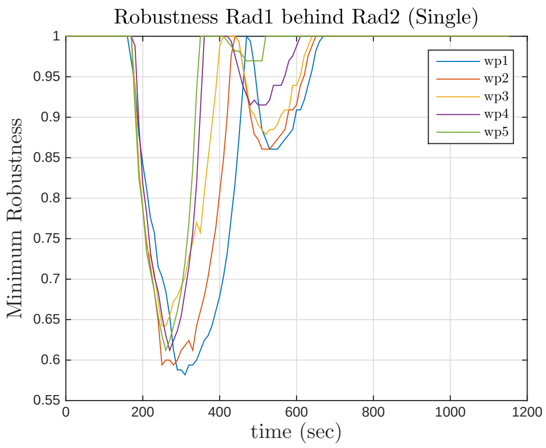


(a) SACR

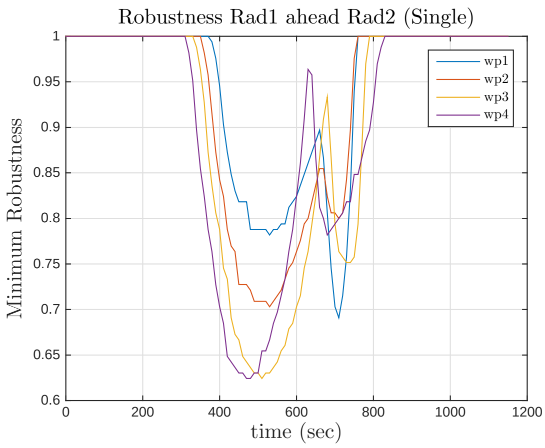


(b) MACR

Figure B.29: Travel Space Representation for 45° conflict angle with intermediate way-points marked.

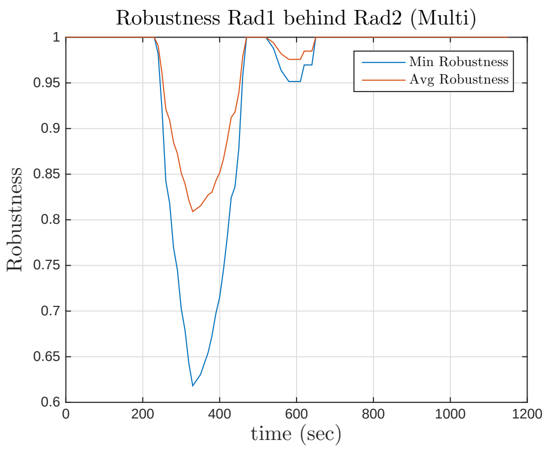


(a) RBT$_{min}$ - Rad1 behind Rad2

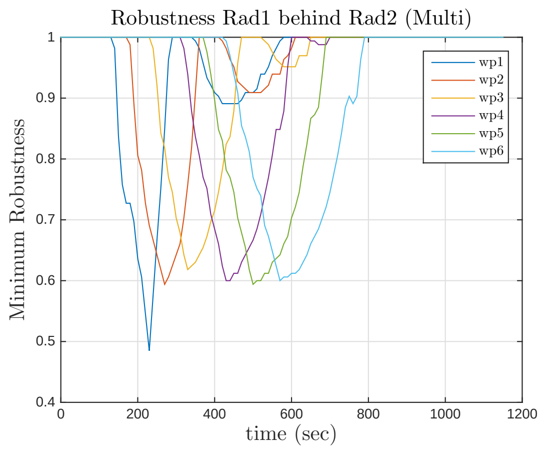


(b) RBT$_{min}$ - Rad1 ahead Rad2

Figure B.30: RBT$_{min}$ for 45° conflict angle with single-aircraft conflict resolution.



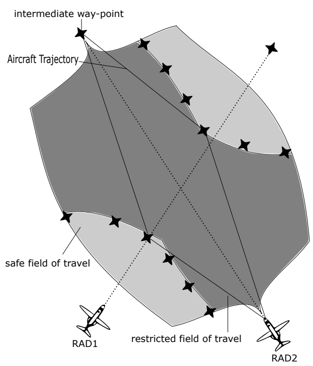
(a) RBT$_{min}$ & RBT$_{avg}$ - Rad1 behind Rad2 for scenario way-point 3



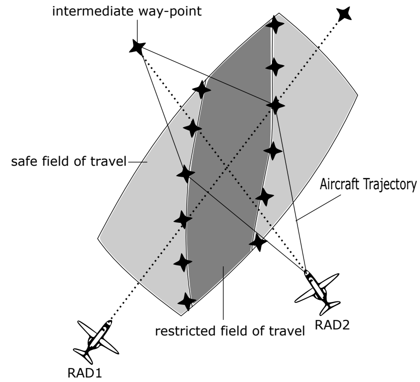
(b) RBT$_{min}$ - Rad1 behind Rad2 all intermediate way-point scenario

Figure B.31: Robustness for 45° conflict angle with multi-aircraft conflict resolution.

B.7.3 60° conflict angle

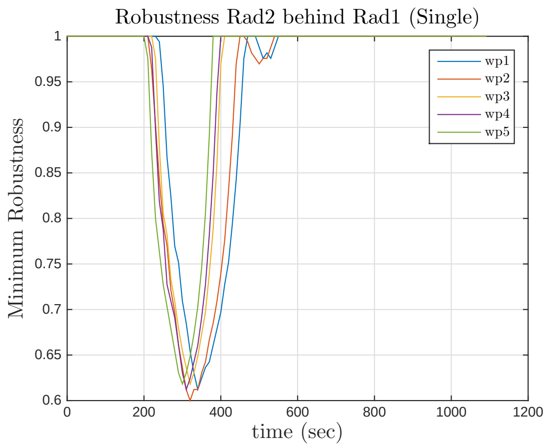


(a) SACR

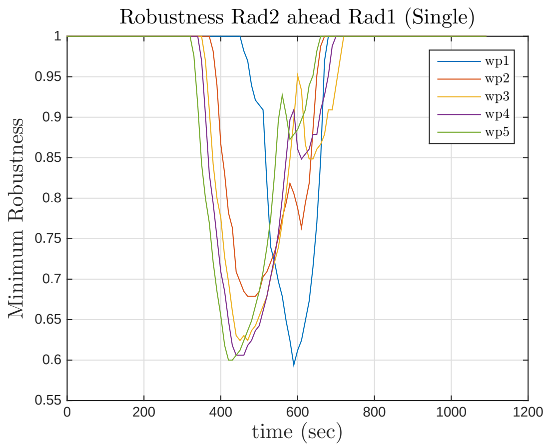


(b) MACR

Figure B.32: Travel Space Representation for 60° conflict angle with intermediate way-points marked.

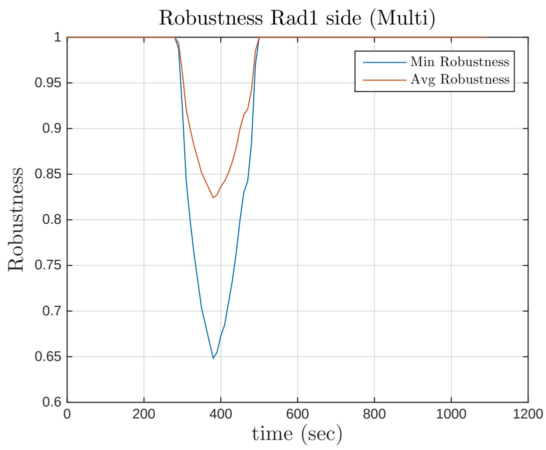


(a) RBT$_{min}$ - Rad2 behind Rad1

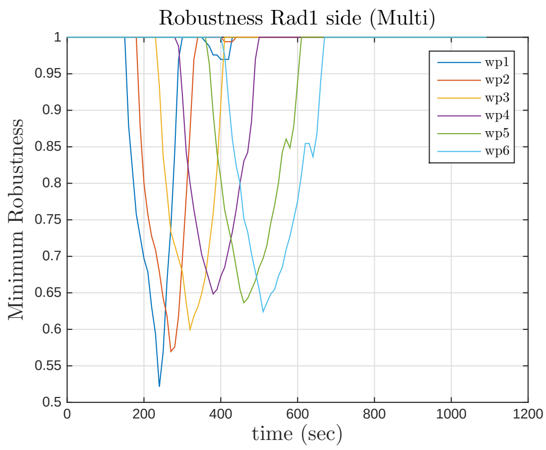


(b) RBT$_{min}$ - Rad2 ahead Rad1

Figure B.33: RBT$_{min}$ for 60° conflict angle with single-aircraft conflict resolution.



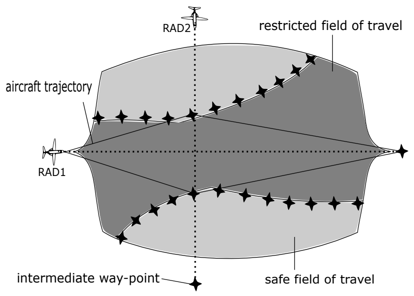
(a) RBT$_{min}$ & RBT$_{avg}$ - Rad2 behind Rad1 way-point 4 scenario



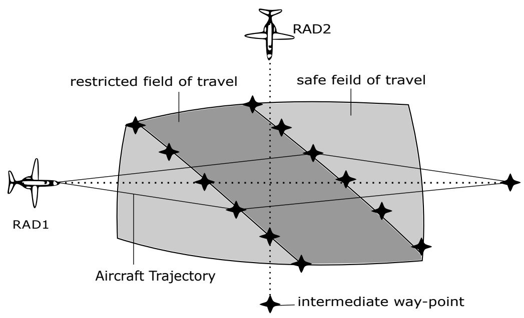
(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate way-point scenario

Figure B.34: Robustness for 60° conflict angle with multi-aircraft conflict resolution.

B.7.4 90° conflict angle

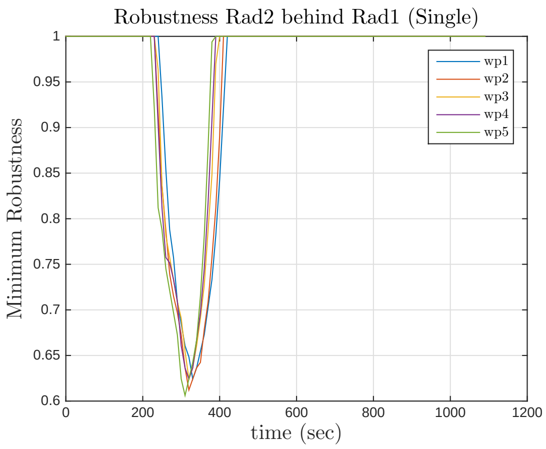


(a) SACR

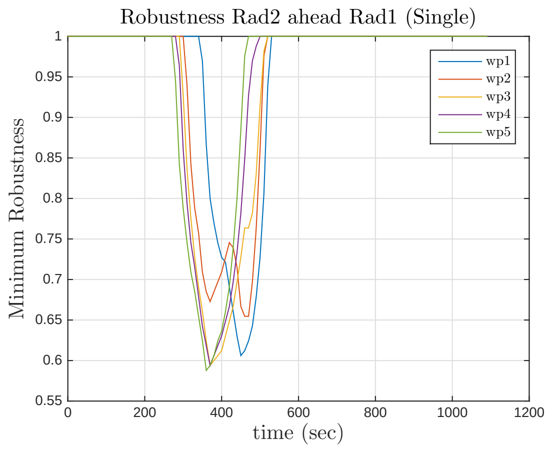


(b) MACR

Figure B.35: Travel Space Representation for 90° conflict angle with intermediate way-points marked.

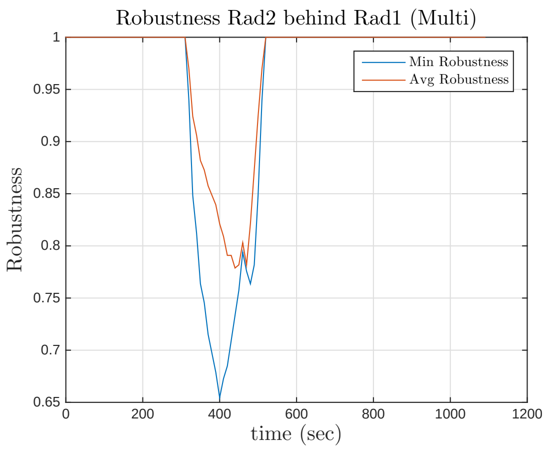


(a) RBT$_{min}$ - Rad2 behind Rad1

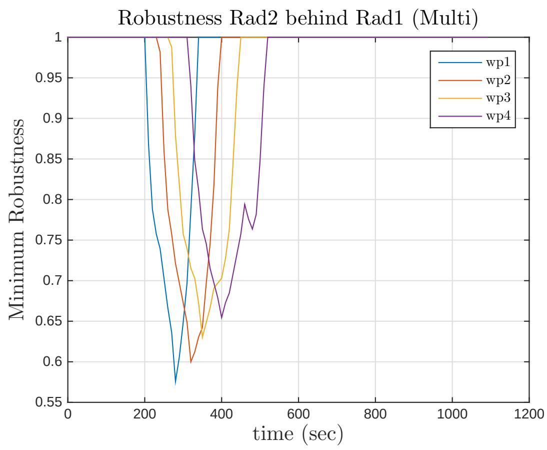


(b) RBT$_{min}$ - Rad2 ahead Rad1

Figure B.36: RBT$_{min}$ for 90° conflict angle with single-aircraft conflict resolution.



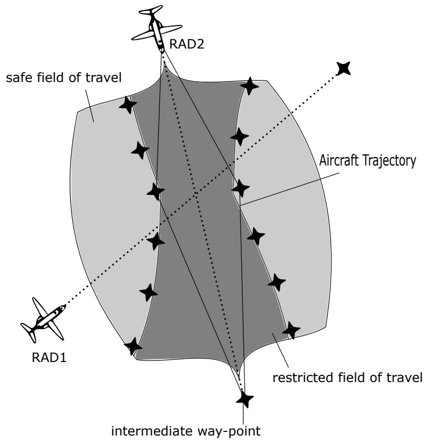
(a) RBT$_{min}$ & RBT$_{avg}$ - Rad2 behind Rad1 way-point 4 scenario



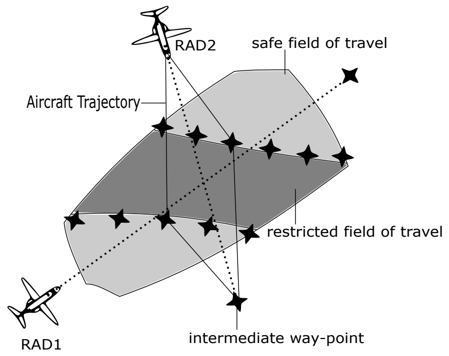
(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate way-point scenario

Figure B.37: Robustness for 90° conflict angle with multi-aircraft conflict resolution.

B.7.5 120° conflict angle

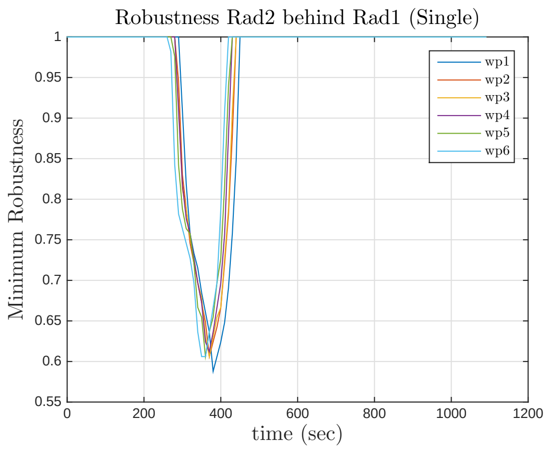


(a) SACR

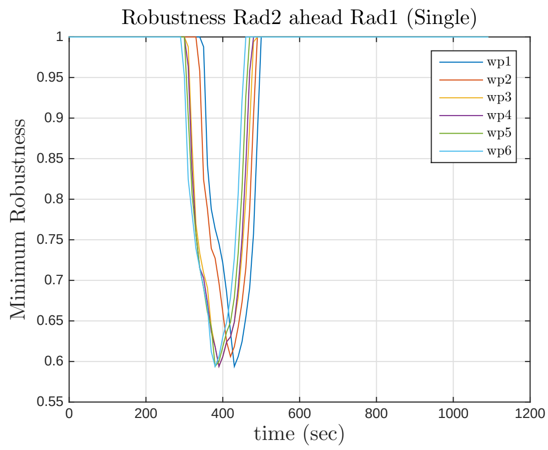


(b) MACR

Figure B.38: Travel Space Representation for 120° conflict angle with intermediate way-points marked.

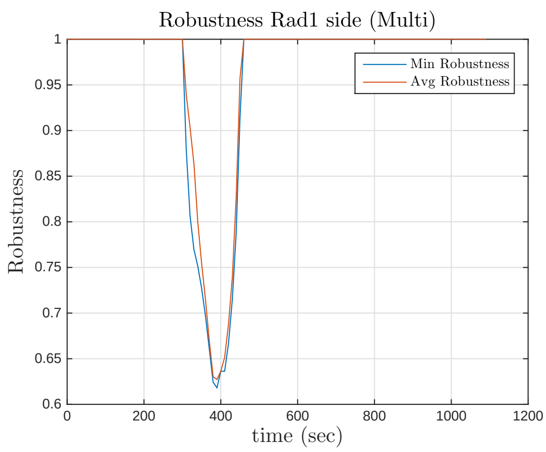


(a) RBT_{min} - Rad2 behind Rad1

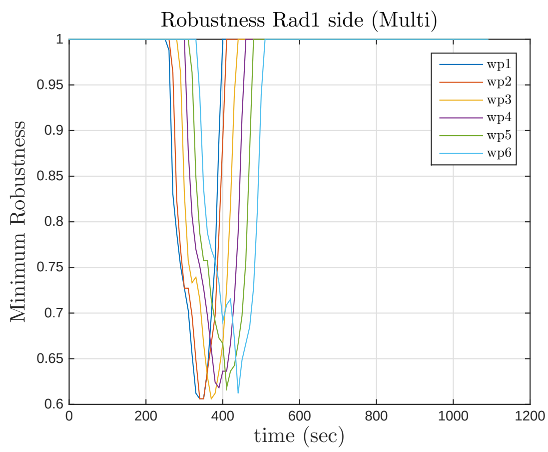


(b) RBT_{min} - Rad2 ahead Rad1

Figure B.39: RBT_{min} for 120° conflict angle with single-aircraft conflict resolution.



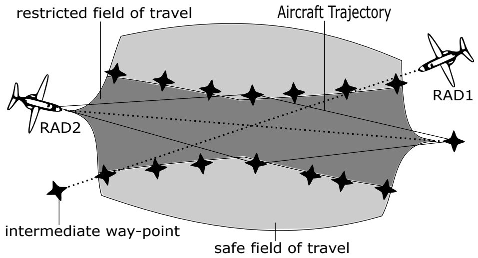
(a) RBT_{min} & RBT_{avg} - Rad2 behind Rad1 way-point 4 scenario



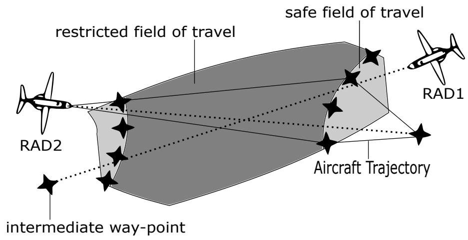
(b) RBT_{min} - Rad2 behind Rad1 all intermediate way-point scenario

Figure B.40: Robustness for 120° conflict angle with multi-aircraft conflict resolution.

B.7.6 150° conflict angle

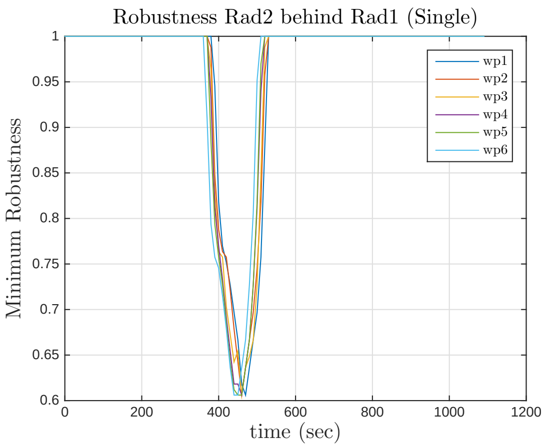


(a) SACR

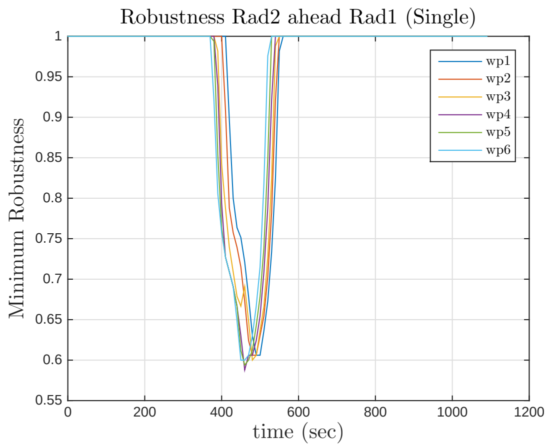


(b) MACR

Figure B.41: Travel Space Representation for 150° conflict angle with intermediate way-points marked.

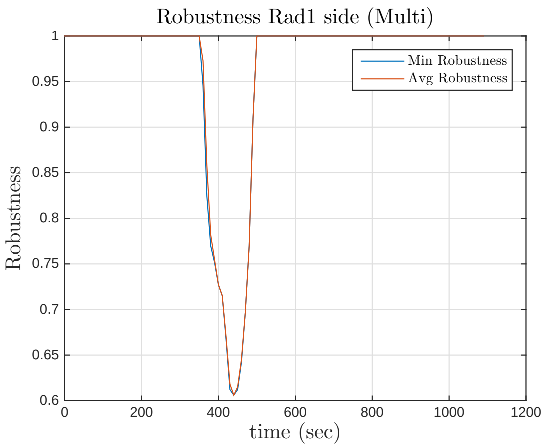


(a) RBT$_{min}$ - Rad2 behind Rad1

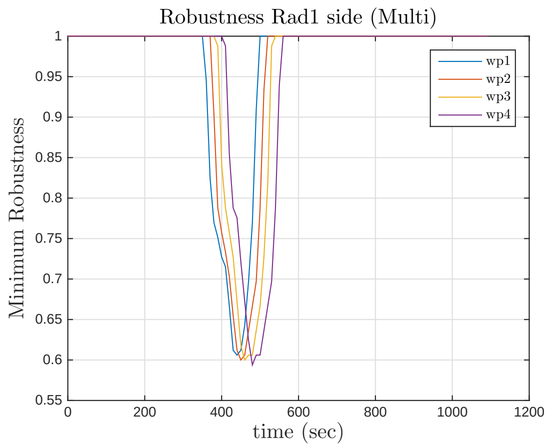


(b) RBT$_{min}$ - Rad2 ahead Rad1

Figure B.42: RBT$_{min}$ for 150° conflict angle with single-aircraft conflict resolution.



(a) RBT$_{min}$ & RBT$_{avg}$ - Rad2 behind Rad1 way-point 1 scenario



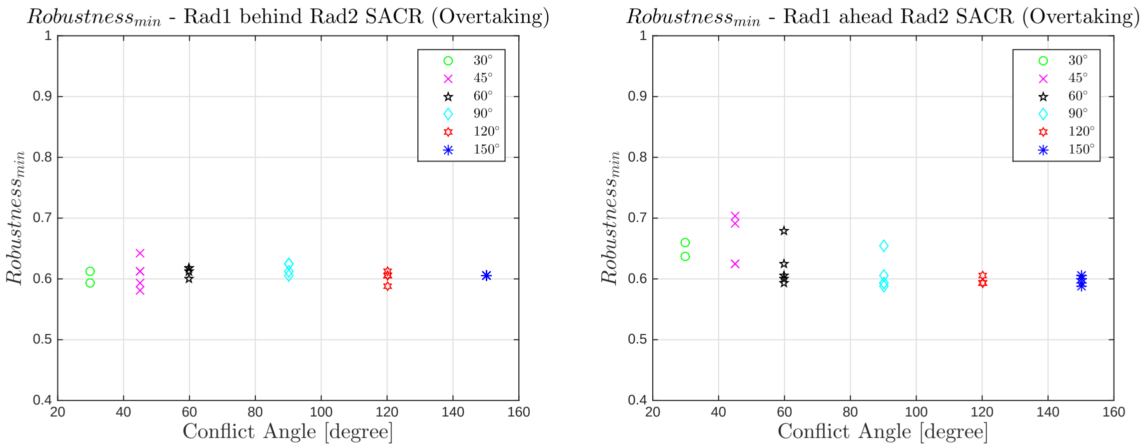
(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate way-point scenario

Figure B.43: Robustness for 150° conflict angle with multi-aircraft conflict resolution.

B.8 Discussion of results

The results from all scenarios with different conflict angles will be discussed in this section. First let us discuss the results for 30° conflict angle. It can be observed from Figure B.26 that the available solutions for control actions are very small. It can be observed from TSR for the SACR case from Figure B.26(a). Figure B.26(b) is the TSR for the MACR case. The available area for maneuvering is better compared to SACR. Also, controller has to be quick at giving control actions. Because the TSR starts shrinking at a faster rate when compared to Section B.5 in previous scenario. Thereby closure rate to conflict is fast since both the aircraft are fast approaching towards each other.

For the 30° conflict angle case, safe area of travel is almost at the extreme edge of the TSR. Which means that the aircraft needs to fly at maximum speed for extended interval of time in order to adhere to strict time constraints (RTA). In doing so, fuel burn will increase and also the aircraft might endure mechanical stress due to aerodynamic effect for prolonged exposure of traveling at high speeds. Rantanen et al., [13] explained in his research paper that, ATCo follow best practice which therefore restricts ordering the aircraft to fly at narrow boundaries which drastically decrease airspace robustness [10, 12, 25]. As discussed in Section B.6, even here the smallest robustness value was calculated for each simulation run (intermediate way-points scenarios). Plots for RBT_{min} for all the scenarios are shown in Figure B.44,



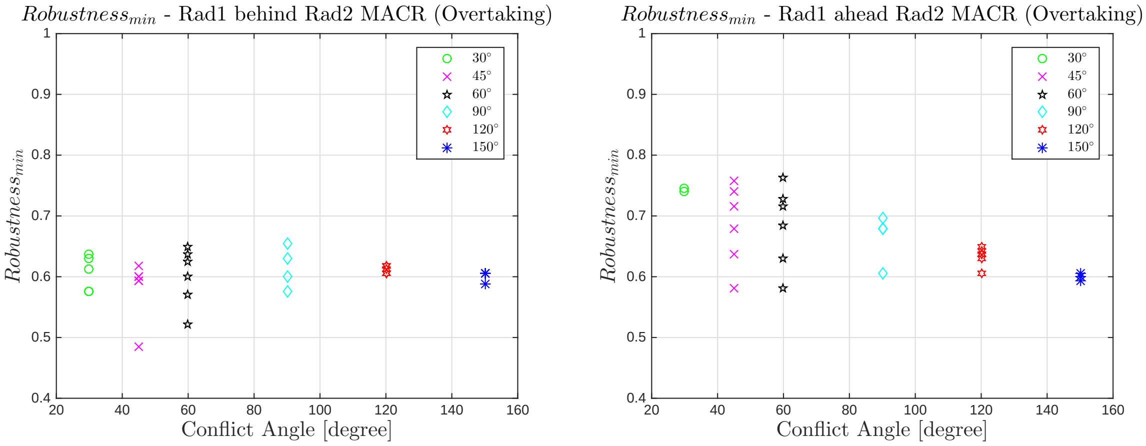
(a) RBT_{min} - Rad1 behind Rad2 scenario

(b) RBT_{min} - Rad1 ahead Rad2 scenario

Figure B.44: RBT_{min} for all the scenario with Single-aircraft conflict resolution (SACR) capability.

RBT_{min} value for slower aircraft going behind faster aircraft scenario is similar for all the conflict angles. Whereas for the other scenario (slower ahead of faster) for lower conflict angles, RBT_{min} value is significantly higher (0.71) than for higher conflict angles (0.6). Although airspace robustness is preserved better in this scenario, robustness plot is stretched for long time period, which thereby increases the monitoring time for the controller (Figure B.27(b)). This can be observed only for lower conflict angles (almost parallel case). For higher conflict angles, $\mathrm{robustness}_{min}$ value is similar for both simulation run (slower aircraft 'behind or ahead' the faster aircraft). Therefore, although mathematically slower aircraft flying in front of faster aircraft preserves airspace robustness better, extended monitoring time for the controllers can be reason for not employing this in real traffic situations.

Similar results are observed in the case of multi-aircraft resolution. When compared with SACR, RBT_{min} value is better for MACR in all the conflict angles. For some simulation runs (placement of intermediate way-point on TSR) robustness value was low (0.49 for 45° & 0.52 for 60° conflict angle). For higher conflict angles RBT_{min} was similar for both SACR and MACR case. Again, it can be observed from the plots that, slower aircraft flying in front of faster aircraft case improved the airspace robustness considerably (0.78). Therefore even in this simulation run, MACR commands resulted in better airspace robustness when compared to SACR.



(a) RBT_{min} - Rad1 behind Rad2 scenario

(b) RBT_{min} - Rad1 ahead Rad2 scenario

Figure B.45: RBT_{min} for all the scenario with multi-aircraft conflict resolution (MACR) capability.

As discussed above, it was evident that robustness was either better than SACR or worse in some cases. After investigating, it was found that RBT_{min} value depends on the position of the intermediate way-point. After careful observations, the position of these way-points were found. In the following figure these wau-points position which gives a low/worse value of robustness is marked as red way-point. In order to maintain high airspace robustness, placement of the new intermediate way-point in these positions have to be avoided.

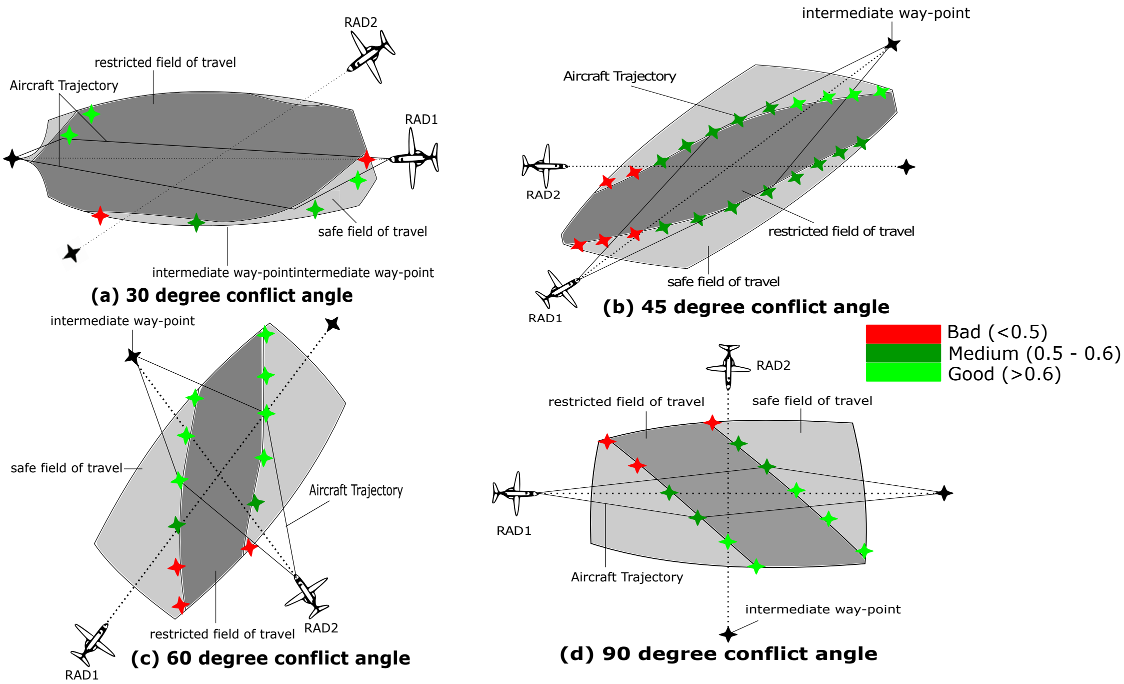


Figure B.46: Way-point position for low RBT_{min} value.

B.8.1 Number of added track miles

Figure B.47 summarizes the average added track miles for all the different conflict angles for both single-aircraft and multi-aircraft resolution case. All the intermediate way-point simulation runs was averaged out in every conflict angle scenario resulting with only one value of added track miles.

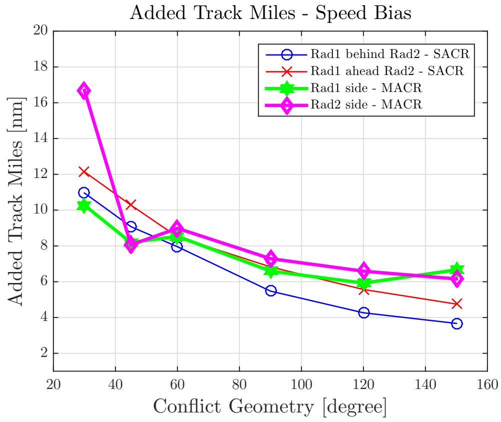
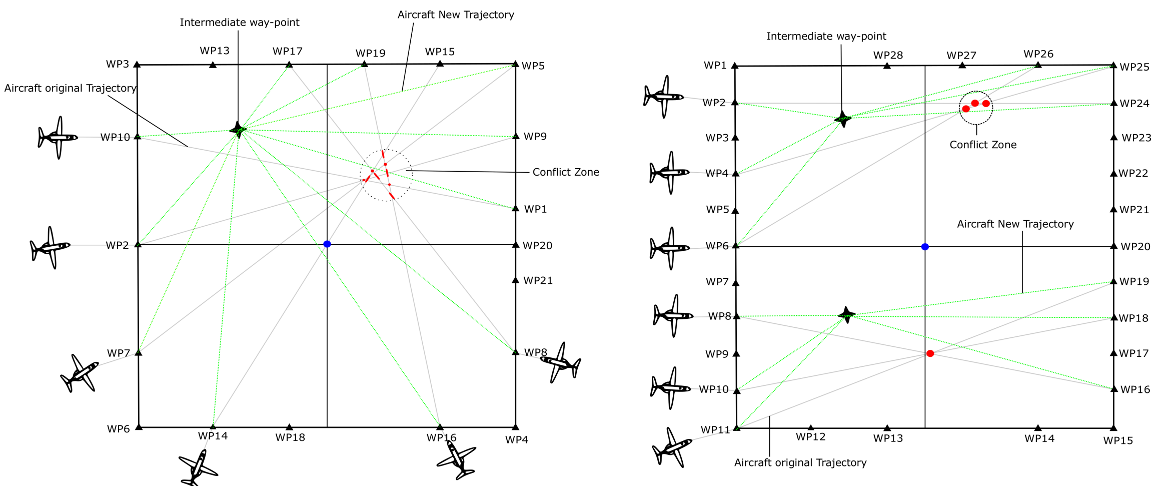


Figure B.47: Average track miles for all the conflict angle scenario.

Similar to as observed with no speed-bias (Section B.6.1) experiment condition, even here also we can observe from Figure B.47 that, for lower conflict angle case the added track miles flown (cumulative) in multi-aircraft case is less when compared to single-aircraft resolution. Whereas for the rest of conflict angle cases, track-miles flown is more. Note that the added track miles gradually decreases with increasing conflict angle. For 30° conflict angle case it is 10.96(SACR) and for 150° conflict angle it is 3.67(MACR). This is due to the fact that, it depends on TSR shape for the above mentioned conflict angle cases. Options (safe filed of travel) available for controllers in 30° conflict case can be visualized from the TSR shown in Figure B.26, it is on the edge of the airspace sector, therefore aircraft has to deviate a lot from their original trajectory in order to maintain safe separation. Whereas for 150° conflict angle, the TSR (Figure B.41) shows safe area of travel very close to aircraft original trajectory, therefore aircraft will not require more deviation resulting in lower number of added track miles for higher conflict angles.

B.9 Limitation of MACR

Air Traffic Controllers (ATCo) always focus on these important factors in order to keep their workload at a minimum: 1) predicting the future projection of traffic , 2) mental model conformance and 3) less complex traffic structure. Even though using MACR will provide a more robust airspace, there are few limitation. In the following section these limitations will be discussed.



(a) Unstructured Traffic (b) Structured Traffic

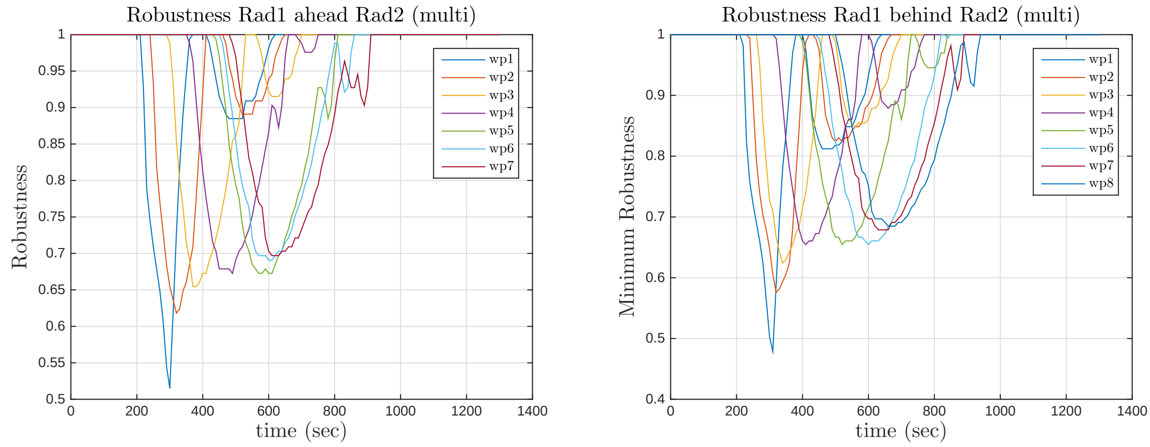
Figure B.48: Projection of Traffic along the airspace for two different traffic condition.

As we can see from Figure B.48(a) when MACR is used, all the aircraft converge towards one merge point. All the conflicts are clustered close to each other. After providing a conflict resolution, trajectories criss cross heading towards one point, it will be difficult to ascertain which aircraft among the group in conflict will arrive first at the converging point (merge point). Therefore, predicting the future traffic structure will not be possible because it will be chaotic.

Whereas in Figure B.48(b) traffic is more structured, since less number of aircrafts are involved, ATCo can readily differentiate which aircraft arrives first compared to others. Therefore, prediction of traffic movement after conflict resolution is simple in this case. In Figure B.48(b) traffic is divided into two streams, meaning aircraft would fly in a fashion which can be understood effortlessly. It is less chaotic compared to Figure B.48(a), where traffic is more complex which in turn increases workload. The controllers will spend more time in analyzing the traffic projection, which will increase the monitoring time. Therefore, while designing the final HITL experiment, care will be taken not to involve scenario with unrealistic workload conditions.

C
ADDITIONAL RESULTS - PA

(I) No Speed Bias - 1. 45° conflict angle

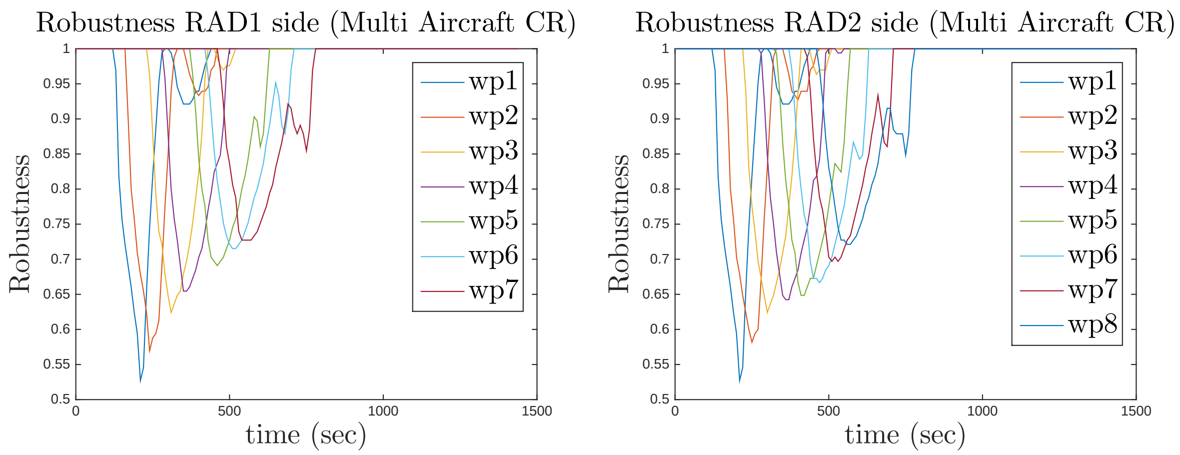


(a) RBT_{min} - Rad1 ahead Rad2 all intermediate way-point scenario

(b) RBT_{min} - Rad1 behind Rad2 all intermediate way-point scenario

Figure C.1: Robustness for 45° conflict angle with multi-aircraft conflict resolution.

2. 60° conflict angle

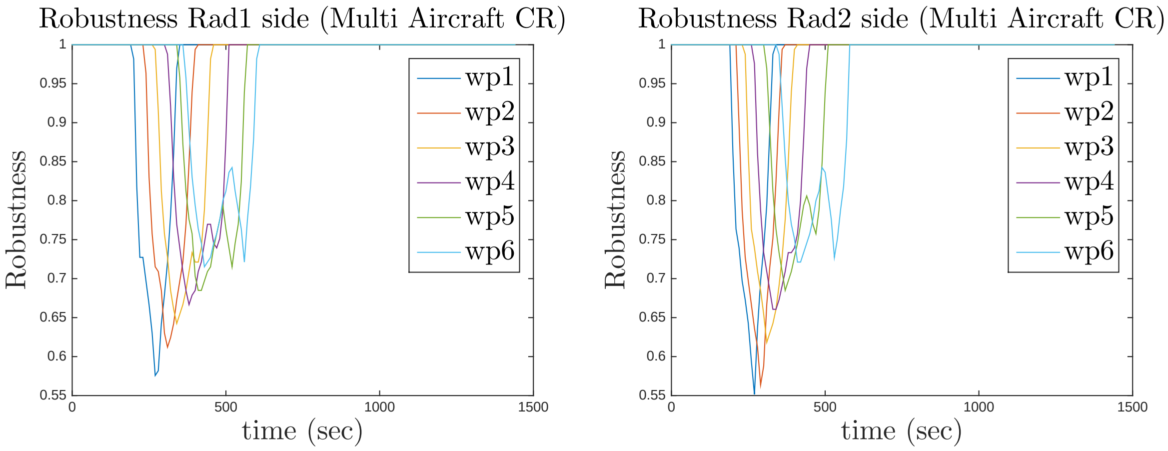


(a) RBT_{min} - Rad1 ahead Rad2 all intermediate way-point scenario

(b) RBT_{min} - Rad1 behind Rad2 all intermediate way-point scenario

Figure C.2: Robustness for 60° conflict angle with multi-aircraft conflict resolution.

3. 90° conflict angle

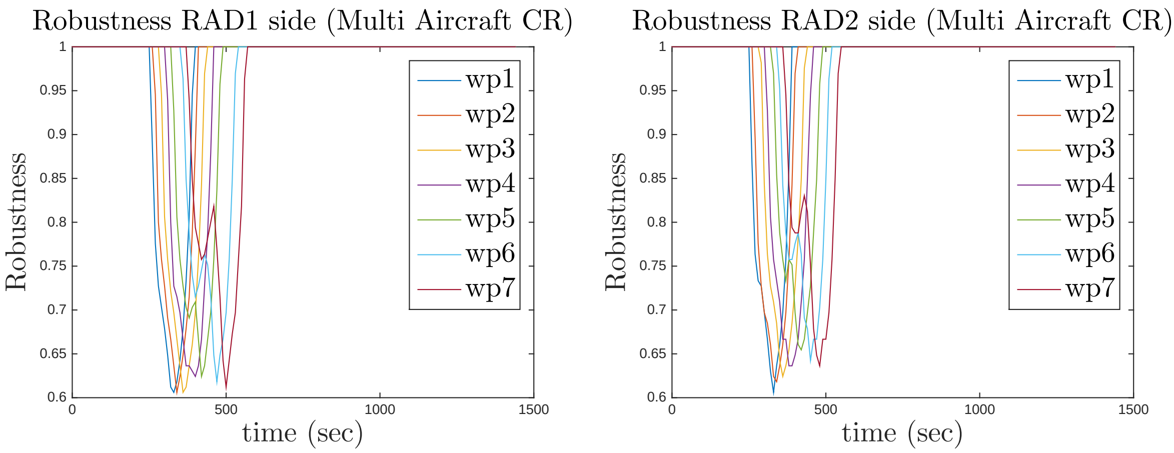


(a) RBT$_{min}$ - Rad1 ahead Rad2 with multi-aircraft conflict resolution

(b) RBT$_{min}$ - Rad1 behind Rad2 with multi-aircraft conflict resolution

Figure C.3: Robustness for 90° conflict angle with multi-aircraft conflict resolution.

4. 120° conflict angle

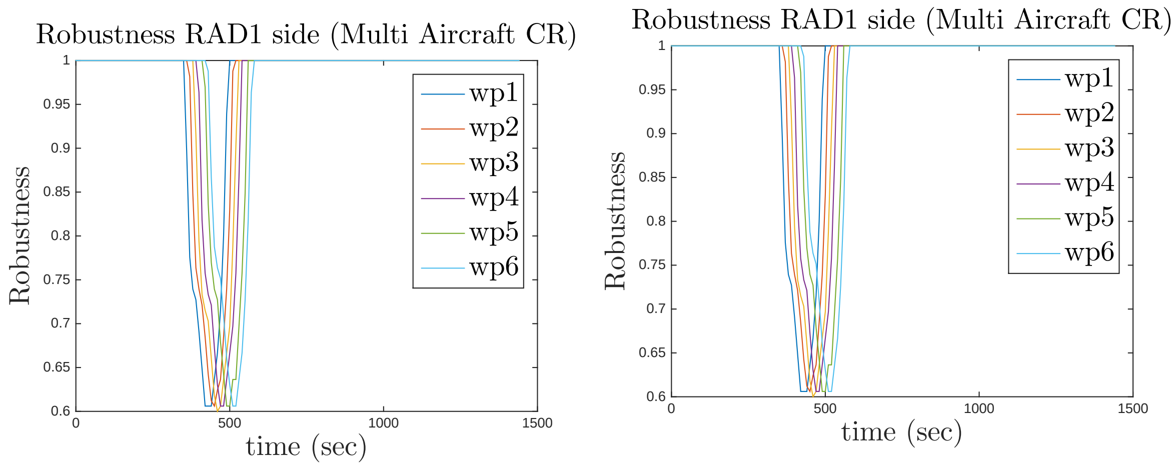


(a) RBT$_{min}$ - Rad1 ahead Rad2 all intermediate way-point scenario

(b) RBT$_{min}$ - Rad1 behind Rad2 all intermediate way-point scenario

Figure C.4: Robustness for 150° conflict angle with multi-aircraft conflict resolution.

5. 150° conflict angle

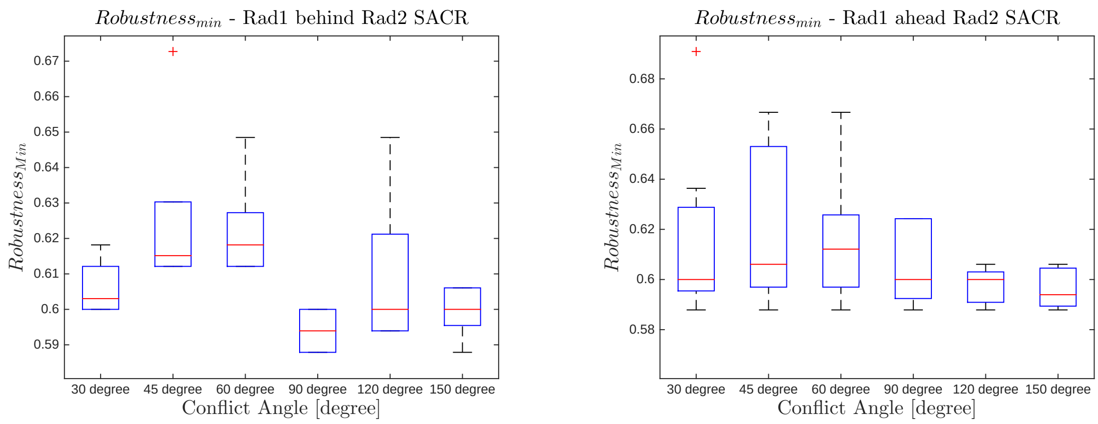


(a) RBT$_{min}$ - Rad2 ahead Rad1 all intermediate wp scenario

(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate wp scenario

Figure C.5: Robustness for 150° conflict angle with multi-aircraft conflict resolution.

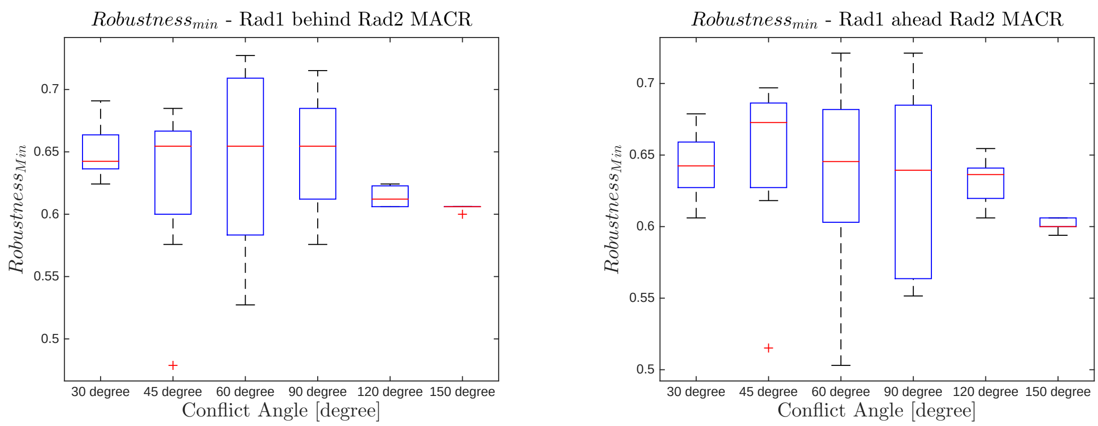
6. Discussion of results



(a) RBT$_{min}$ - Rad1 behind Rad2 scenario

(b) RBT$_{min}$ - Rad1 ahead Rad2 scenario

Figure C.6: RBT$_{min}$ for all the scenario with Single-aircraft conflict resolution (SACR) capability.



(a) RBT$_{min}$ - Rad1 behind Rad2 scenario

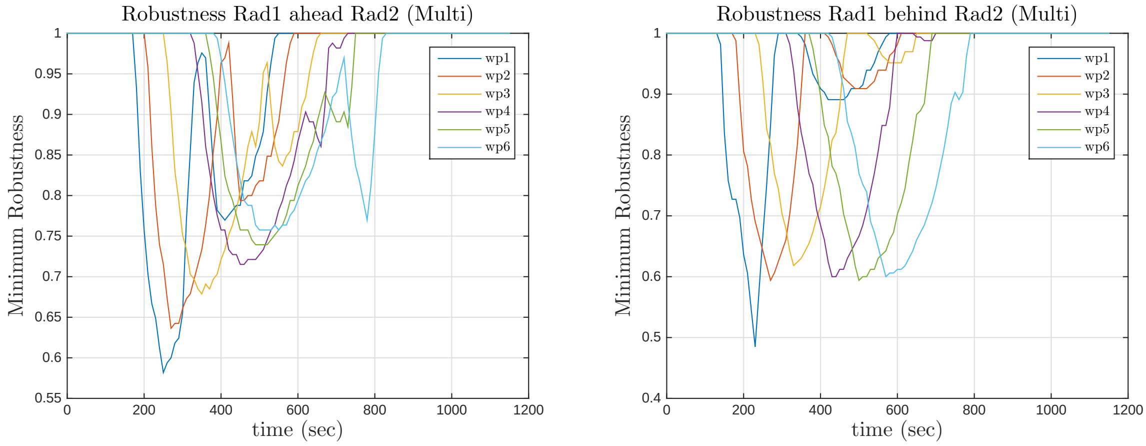
(b) RBT$_{min}$ - Rad1 ahead Rad2 scenario

Figure C.7: RBT$_{min}$ for all the scenario with multi-aircraft conflict resolution (MACR) capability.

Robustness Plots for different conflict angles

(II) Speed Bias

1. 45° conflict angle

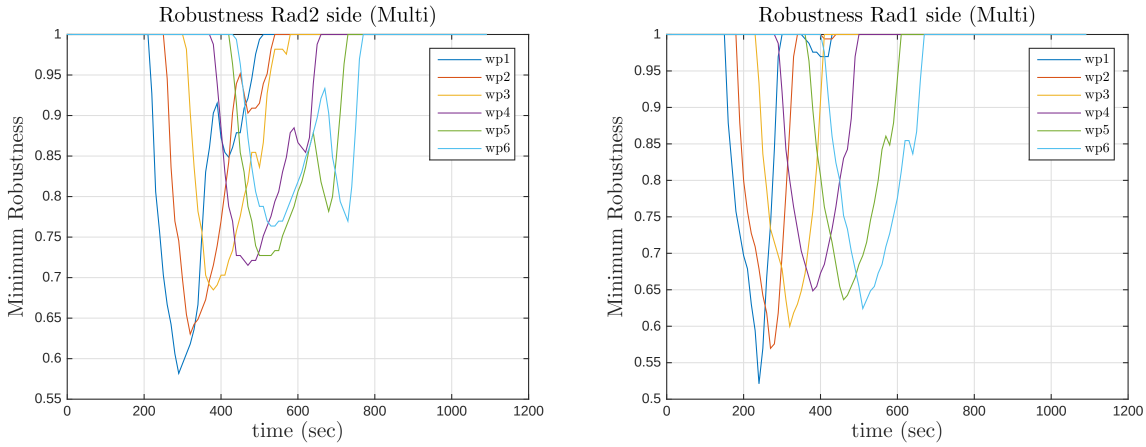


(a) RBT_{min} - Rad1 ahead Rad2 all intermediate way-point scenario

(b) RBT_{min} - Rad1 behind Rad2 all intermediate way-point scenario

Figure C.8: Robustness for 45° conflict angle with multi-aircraft conflict resolution.

2. 60° conflict angle

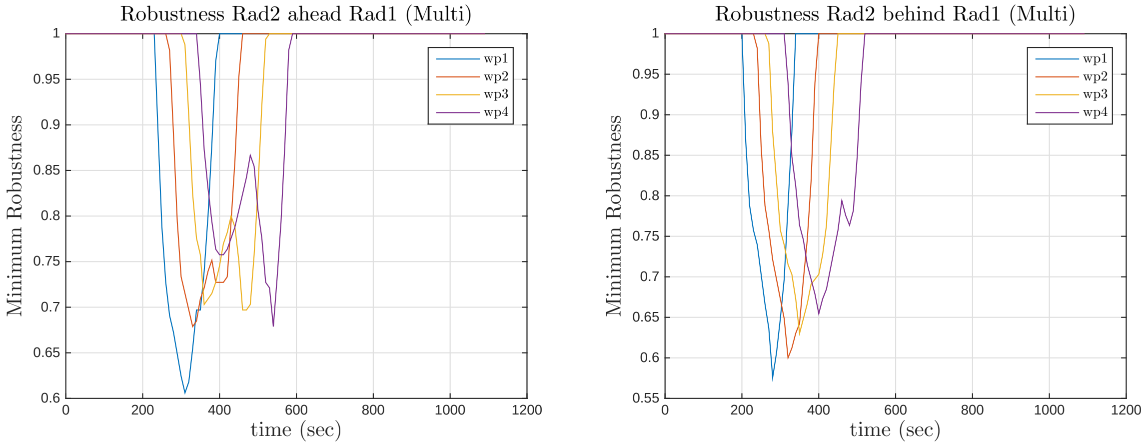


(a) RBT_{min} - Rad2 ahead Rad1 all intermediate way-point scenario

(b) RBT_{min} - Rad2 behind Rad1 all intermediate way-point scenario

Figure C.9: Robustness for 60° conflict angle with multi-aircraft conflict resolution.

3. 90° conflict angle

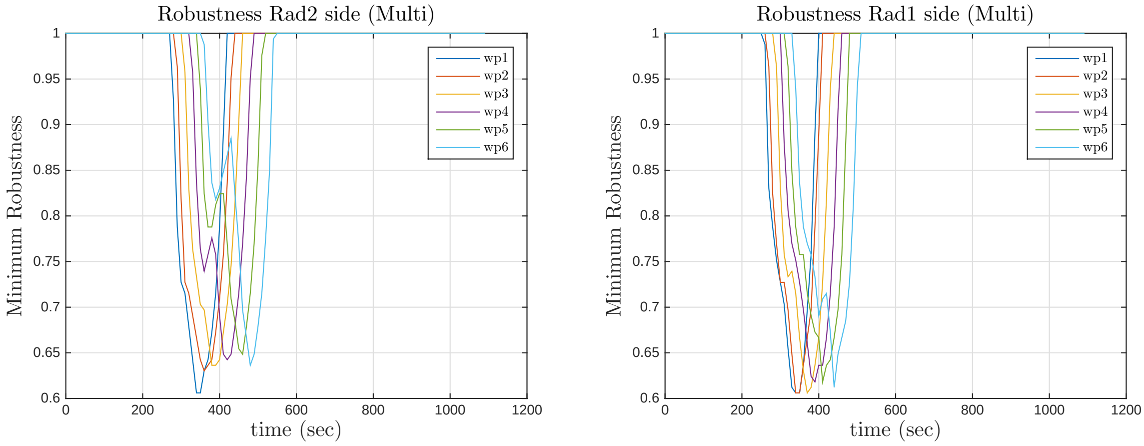


(a) RBT$_{min}$ - Rad2 ahead Rad1 all intermediate way-point scenario

(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate way-point scenario

Figure C.10: Robustness for 90° conflict angle with multi-aircraft conflict resolution.

4. 120° conflict angle

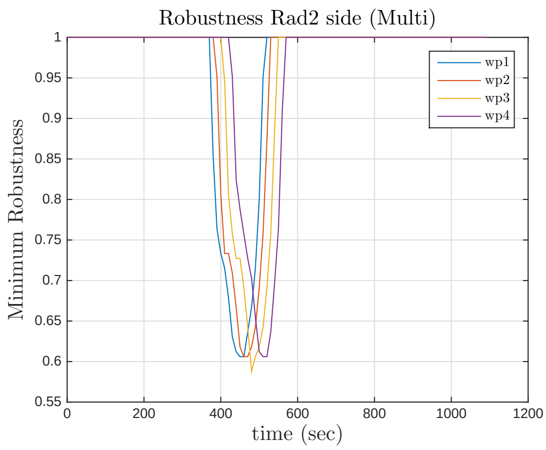


(a) RBT$_{min}$ - Rad2 ahead Rad1 all intermediate way-point scenario

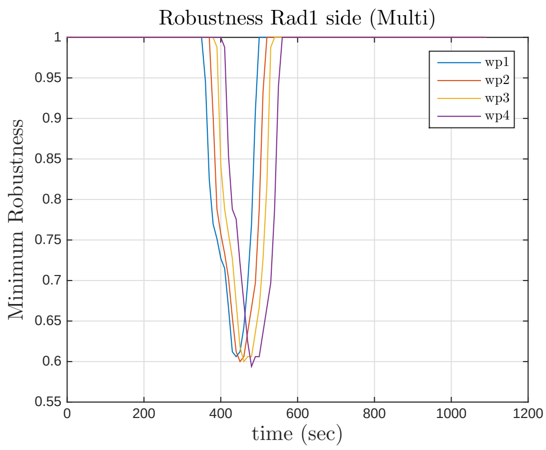
(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate way-point scenario

Figure C.11: Robustness for 120° conflict angle with multi-aircraft conflict resolution.

5. 150° conflict angle



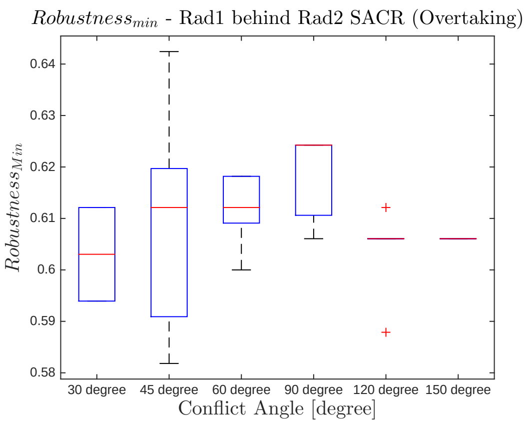
(a) RBT$_{min}$ - Rad2 ahead Rad1 all intermediate way-point scenario



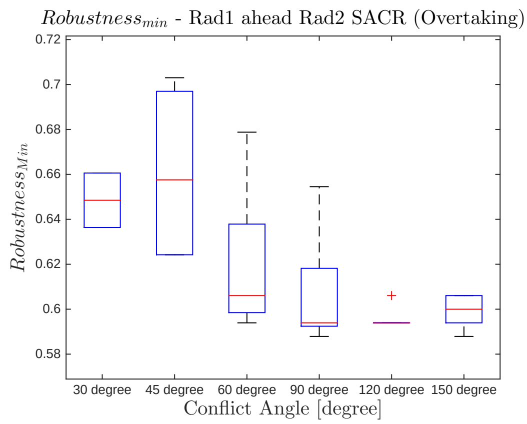
(b) RBT$_{min}$ - Rad2 behind Rad1 all intermediate way-point scenario

Figure C.12: Robustness for 150° conflict angle with multi-aircraft conflict resolution.

6. Discussion of results

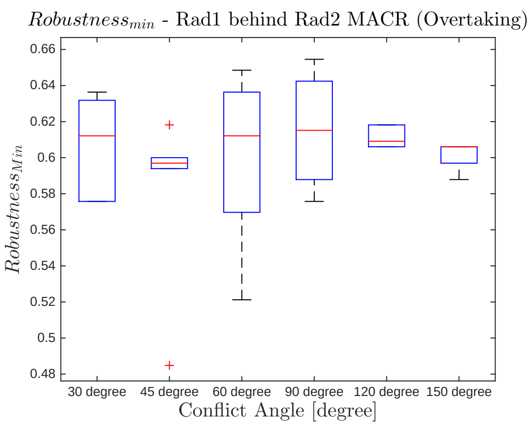


(a) RBT$_{min}$ - Rad1 behind Rad2 scenario

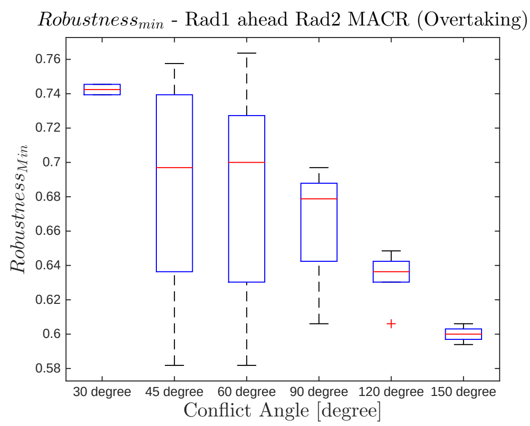


(b) RBT$_{min}$ - Rad1 ahead Rad2 scenario

Figure C.13: RBT$_{min}$ for all the scenario with Single-aircraft conflict resolution (SACR) capability.



(a) RBT$_{min}$ - Rad1 behind Rad2 scenario



(b) RBT$_{min}$ - Rad1 ahead Rad2 scenario

Figure C.14: RBT$_{min}$ for all the scenario with multi-aircraft conflict resolution (MACR) capability.

D

Pre-experiment Briefing

Information to the Participant

General information

The experiment that you are participating in today is a 4D trajectory Air Traffic Management (ATM) research tool called Travel Space Representation (TSR) being developed in the department of Control & Simulation at the TU Delft Aerospace Engineering Faculty. The aim of this research is to design a Joint Cognitive System (JCS), or human-machine ensemble, to support perturbation management in the future. This is one of many research initiatives around the world that aim to address future challenges within the ATM domain for the near future and beyond.

The experiment that you are participating in is intended to test a novel representation for supporting off nominal operations (perturbation management) in future 4D air traffic management. The aim of the experiment is to evaluate both single-aircraft conflict resolution (SACR) and multi-aircraft conflict resolution (MACR) capability that can support future trajectory-based perturbation management effectively in an en-route ATM environment.

Your participation

Your participation is completely voluntary and you have the right to withdraw from the study at any moment without explanation. The recorded data are made anonymous, and are to be used solely for academic purposes.

The overall experiment

During the experiment run you will be asked to safely manage en-route traffic with the help of the Travel Space tool. There are six scenarios with varying traffic and restrictions placed upon the sector. Your task is to actively control the traffic by manipulating the (4D) routes of aircraft using the Travel Space representation with the help of the Travel Space tool. You will thus have two responsibilities,

1. Maintain a separation of at least 5 NM between aircraft at all times (the minimum required separation).
2. Re-route aircraft such that they will never fly inside/through a restricted no-fly zone.

Please note that the system you are using presents one possible way of how aircraft might be handled in the future. This means that you might conduct tasks in a way that differs from how an en-route air traffic controller works today.

Timeline for the experiment

The overall timeline for the experiment is depicted in the table below.

Activity	Estimated duration
Introduction to the experiment	5 min
Training session	45 - 60 min
Break	10 min
Experiment run 1	15 min
Experiment run 2	15 min
Experiment Run 3	15 min
Break	10 min
Experiment Run 4	15 min
Experiment Run 5	15 min
Experiment Run 6	15 min
Debrief	10 – 15 min
Questionnaires (online)	5 min

BRIEF

There are two ways to re-route aircraft and provide conflict resolutions in this experiment:

1. **Single-Aircraft Conflict Resolution (SACR)**: when this resolution capability is used, the TSR of only one aircraft will be available and therefore only the trajectory of one aircraft will change.

2. **Multi-Aircraft Conflict Resolution (MACR)**: when this resolution capability is used, the TSR of all selected aircraft will be available. Therefore, the trajectories of all aircrafts will change.

More information on the above two capabilities will be provided during training.

Training

Before the experimental runs will start, you will spend approximately 30-60 minutes training how to operate the system. Please make sure that you ask all questions that you have in relation with the system's functionality during the training so that you feel familiarized with the workings of the system, and feel well prepared for the experimental runs.

Apparatus

The experiment will be conducted in the Air Traffic Management Laboratory (ATM Lab) on 2nd floor of the SIMONA building. LCD screens will be used to simulate ATC radar screen (See figure below). As a subject, you can interactively control aircraft trajectories using the mouse and keyboard.

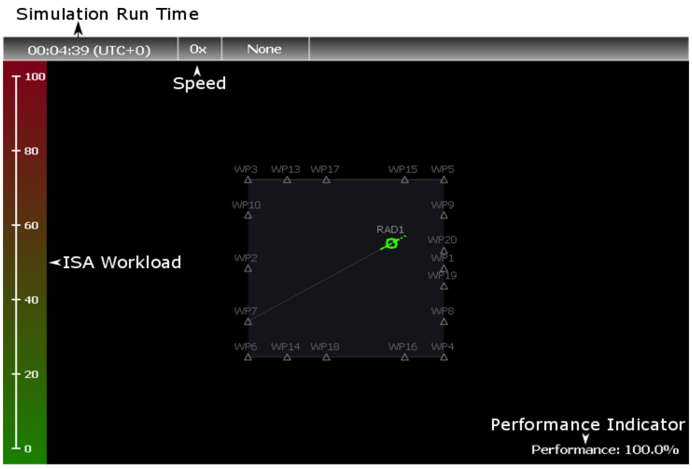


Figure1. Screenshot of simulated radar screen

Scenario time & questionnaires

The scenarios during training and the experiment are in so-called scenario time, which is representing one to four times the speed of real-time. This means, for example, that each scenario in the experiment will last approximately 15 minutes, which represents about 60 minutes in scenario time.

Instantaneous Self Rating of Workload (ISA)

Every 60 seconds an Instantaneous Self Rating (ISA) Scale will pop up on the left-hand side of the screen. This scale is used to obtain your rating of the Workload experienced at that point in time of the scenario. The scale will be accompanied by an audio signal to indicate that a rating should be submitted.

Airspace & traffic

The active en-route sectors in the experiment are artificial sectors and constructed specifically for this experiment. All aircraft movements are restricted to the horizontal plane (e.g., same flight level). Therefore, separating aircraft vertically will *not* be possible. All aircraft resemble a generic type of medium-sized commercial airliner and have *equal* performance (e.g., same speed range). During the training and the experiment, you are free to manage the traffic, manipulate the routes (and speeds) of the aircraft in whichever way you prefer.

Debrief and Questionnaire

During this session you will be free to comment on your experience of using the system.

E

BACKGROUND QUESTIONNAIRE AND CONSENT FORM

Subject ID: __________

Background Questionnaire

This questionnaire has the purpose to collect background information about the participants of the Travel Space evaluation experiment.

Age:

Gender: M / F

What is the highest degree or level of education you have completed?
If currently enrolled, mark the previous highest degree received.

- o High school degree
- o Bachelor's degree (e.g. BA, BSc)
- o Master's degree (e.g. MA, MSc, MBA)
- o Doctorate degree (PhD)
- o Other, please specify:

How regularly do you play computer, video games, or smartphone games that are related to air traffic control (ATC)?

- o Never
- o Less frequent than once a month
- o Monthly
- o Weekly
- o Daily

Please indicate which ATC game(s) and approximately how frequently you play.
(ie., hours/week, hours/month, etc.)

Game: ______/______
Game: ______/______
Game: ______/______

Have you participated in any experimental study concerning Air Traffic Management prior to the Travel Space evaluation?

- o No
- o Yes, please indicate which studies:

What is your relation to the Air Traffic Control domain?

- o Actively working as an air traffic controller
- o Student within an ATC-related education program
- o Student at Aerospace Engineering
- o Student from another faculty; please specify______________________________

How would you describe your knowledge about Air Traffic Control operations?

- o Poor
- o Fair
- o Good
- o Excellent

Subject ID: _______________

Participant Consent Form

The aim of the Travel Space tool is to design a Joint Cognitive System (JCS), or human-machine ensemble, to support perturbation management in future Air Traffic Control. The aim of the experiment is thus to evaluate both single-aircraft conflict resolution (SACR) and multi-aircraft conflict resolution (MACR) capability that can support future trajectory-based perturbation management effectively in a en-route ATM setting.

During the experimental runs we will record various data. You will also be requested to answer a number of questions and questionnaires before, during and after the experiment. Your participation in this experiment is completely voluntary and you have the right to withdraw from the study at any time without having to give any explanation. In that case all data connected to you as an individual will be deleted.

Various types of data will be recorded during the experimental runs. These data, besides recordings of the traffic image will also include ISA (Indicated Self-Assessment) ratings of workload, situation awareness, and performance score. The entire experiment will also involve talk-loud sessions, therefore a video camera will record both the simulation screen to capture traffic manipulation and audio of the controller explaining the reason to have solved the traffic manipulation in a particular manner. These will only be used for project-related documentation. Recorded data will be separated from your identity; at no time, neither now, nor in the future, will any information you provide be published that allows you as an individual to be identified. We certify to treat collected data according to good practice and follow sound ethical rules.

If you have any questions or comments concerning this study you can ask the experiment researcher.

The experiment researcher has described the purpose of the study and I know the preconditions that apply. Possible questions I had have been answered satisfactory. I am aware that behaviour related data and questionnaires will be collected and analysed. I know that I can decide to leave the experiment at any time without the need to provide any explanation.

I ____________________________ agree and participate voluntarily in this study.

Name (clear writing)

Signature: ____________________________ Date: ____________

F

Order of the Experiments

In order to randomize the experiment conditions, a latin square distribution was used to prevent any carry over effects in the measurement runs. Figure F.1 shows the Latin square distribution for the six experiment conditions. Participant 113 (thirteen) was given the same experiment conditions as participants 103.

Latin square

	1	2	3	4	5	6
P1	Scenario1	Scenario5	Scenario11	Scenario3	Scenario7	Scenario9
P2	Scenario6	Scenario12	Scenario4	Scenario8	Scenario10	Scenario2
P3	Scenario11	Scenario3	Scenario7	Scenario9	Scenario1	Scenario5
P4	Scenario4	Scenario8	Scenario10	Scenario2	Scenario6	Scenario12
P5	Scenario7	Scenario9	Scenario1	Scenario5	Scenario11	Scenario3
P6	Scenario10	Scenario2	Scenario6	Scenario12	Scenario4	Scenario8
P7	Scenario2	Scenario6	Scenario12	Scenario4	Scenario8	Scenario10
P8	Scenario5	Scenario11	Scenario3	Scenario7	Scenario9	Scenario1
P9	Scenario12	Scenario4	Scenario8	Scenario10	Scenario2	Scenario6
P10	Scenario3	Scenario7	Scenario9	Scenario1	Scenario5	Scenario11
P11	Scenario8	Scenario10	Scenario2	Scenario6	Scenario12	Scenario4
P12	Scenario9	Scenario1	Scenario5	Scenario11	Scenario3	Scenario7

P=Participant

Figure F.1: Latin Square distribution of the experiment conditions

In addition to the six conditions, each scenario was further rotated. They were rotated such that the participants would not recognize the traffic structure from other experiment runs. Further in each of the twelve scenarios the aircraft ID's and way-points names were also changed in order to eliminate scenario recognition. Therefore in oder to balance the latin square 12 participants was required.

The order of rotation is shown in Table F.1.

Table F.1: Experiment Scenarios rotation

Condition	Rotated	Condition
Scenario1	90°	Scenario2
Scenario3	180°	Scenario4
Scenario5	180°	Scenario6
Scenario7	180°	Scenario8
Scenario9	90°	Scenario10
Scenario11	180°	Scenario12

G

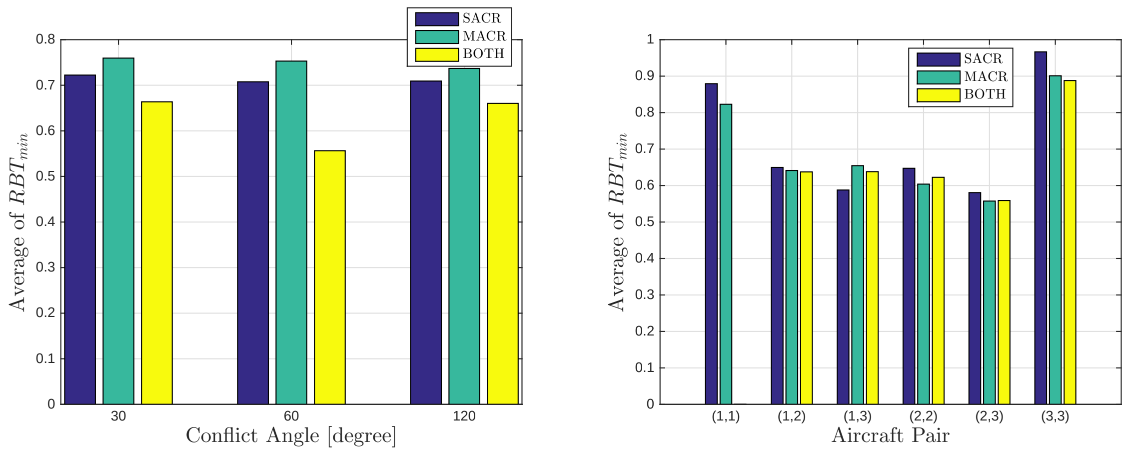
ADDITIONAL EXPERIMENT RESULTS AND ANALYSIS

In this appendix the additional results from the experiment which could not be shown in the masters-thesis paper due to space concerns has been presented. Additional statical analysis on robustness value with the influence of forbidden zone are presented at the end of this appendix section.

G.1 Without considering forbidden zone (no-go area)

G.1.1 Robustness

In this section the average robustness with respect to conflict angles and aircraft pairs for all the experiment conditions are shown. In the data analysis while calculating the robustness value, the influence of forbidden zone (no-go area) was not considered.



(a) Conflict Angle

(b) Aircraft Pair

Figure G.1: Bar plots of Average RBT_{min}.

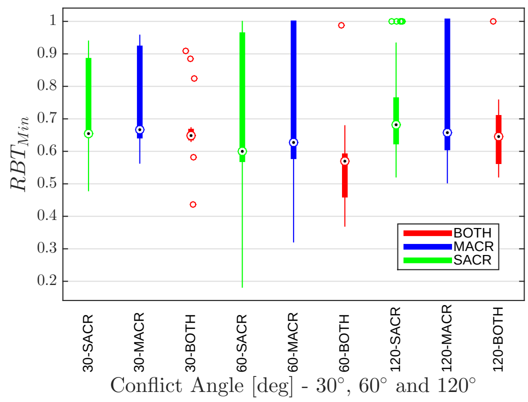
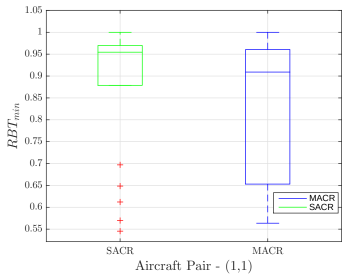
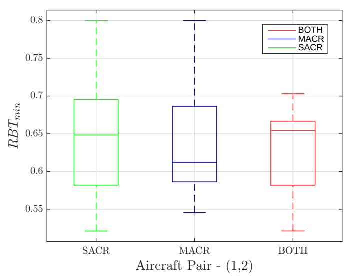


Figure G.2: Box plot of RBT_{min} for all the Conflict Angles.

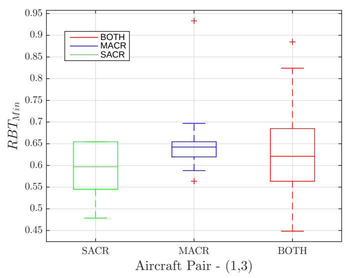
The box plots of minimum robustness (RBT_{min}) for all the aircraft pairs are shown below.



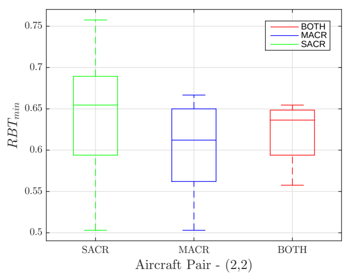
(a) (1,1)



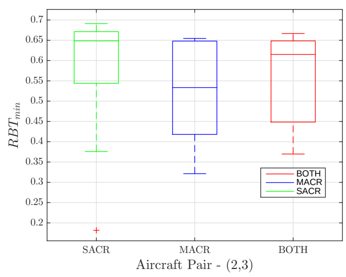
(b) (1,2)



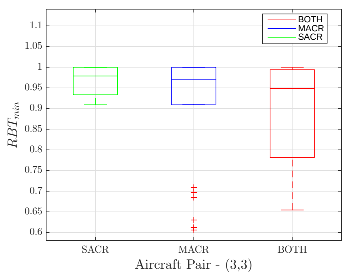
(c) RBT_{min} - (1,3)



(d) (2,2)



(e) (2,3)



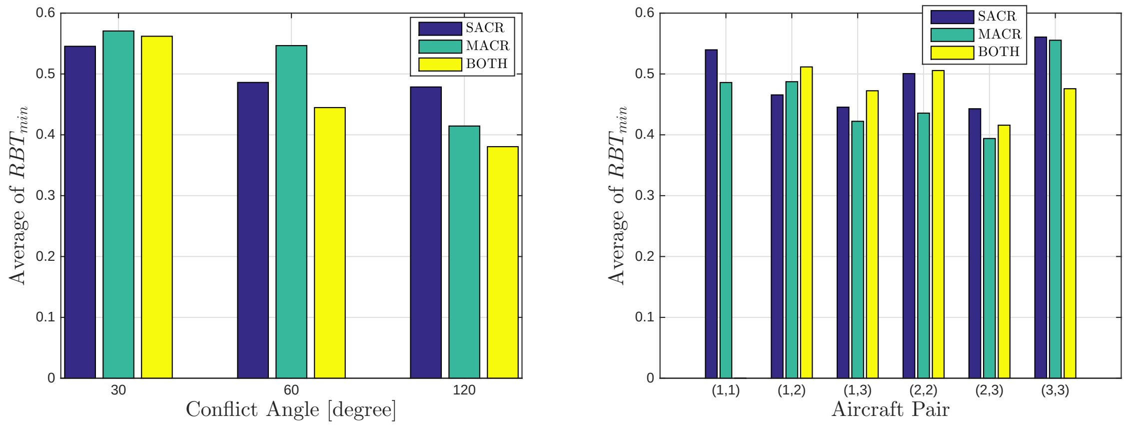
(f) RBT_{min} - (3,3)

Figure G.3: Box plots of RBT_{min} - aircraft pairs.

G.2 With considering forbidden zone (no-go area)

G.2.1 Robustness (Airspace flexibility)

In this section the average robustness with respect to conflict angles and aircraft pairs for all the experiment conditions are shown. While calculating the robustness value in the data analysis the influence of forbidden zone (no-go area) was considered. Hence we can observe in the plots that the robustness value is lower when compared to the plots shown in Section G.1.1.

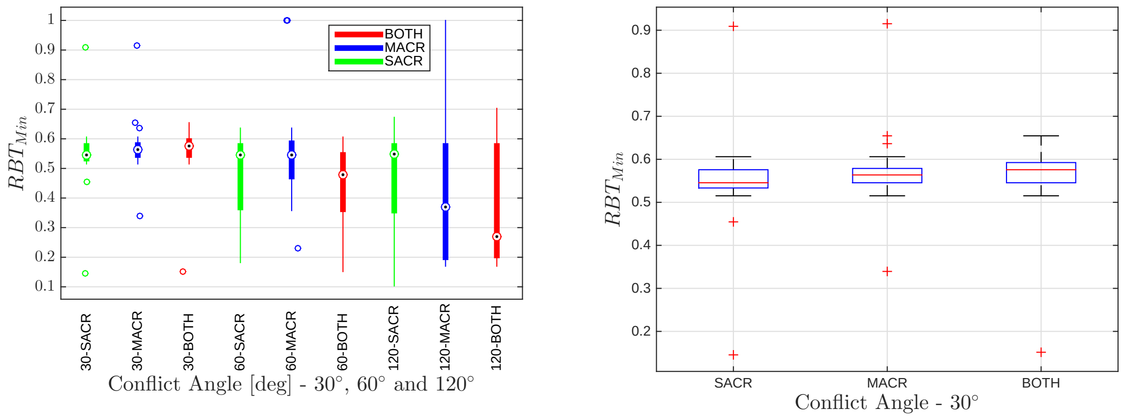


(a) Conflict Angle

(b) Aircraft Pair

Figure G.4: Bar plots of Average RBT_{min}, with the influence of forbidden zone.

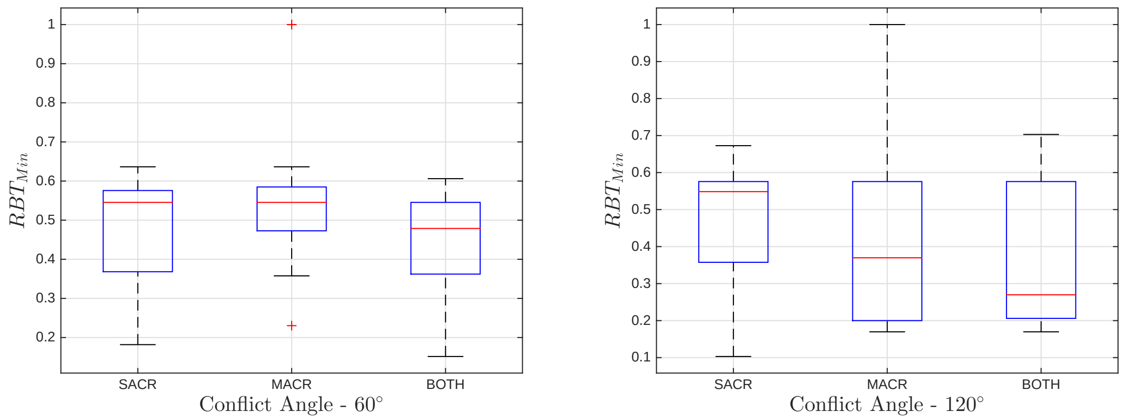
The box plots of minimum robustness (RBT_{min}) for all the conflict angles [deg] are shown below.



(a) (Box Plot for all the conflict angles)

(b) (30°)

Figure G.5: Box plots of RBT_{min} - Conflict angles[deg], with the influence of forbidden zone.

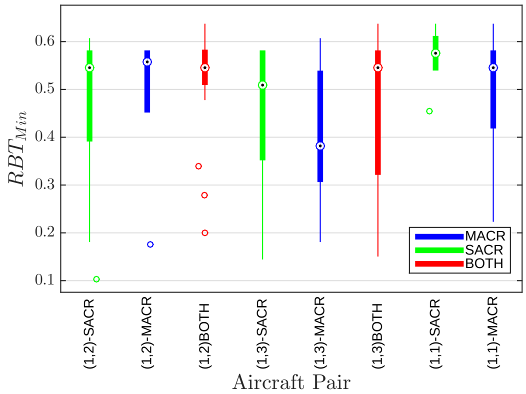


(a) (60°)

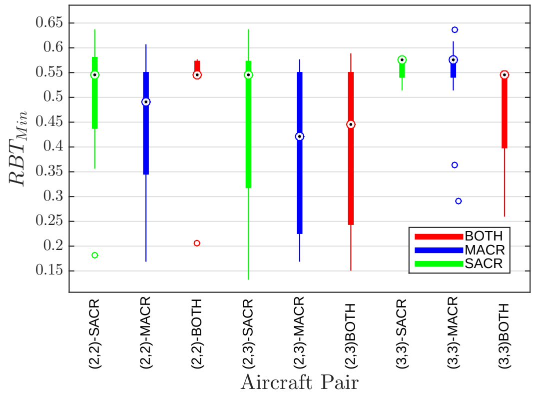
(b) (120°)

Figure G.6: Box plots of RBT_{min} - Conflict angles, with the influence of forbidden zone.

The box plots of minimum robustness (RBT_{min}) for all the aircraft pair is shown below.

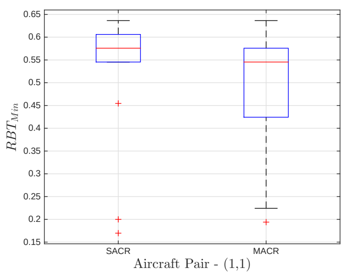


(a) For first three aircraft pairs

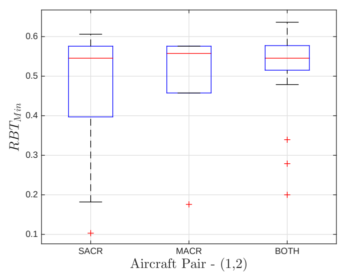


(b) For last three aircraft pairs

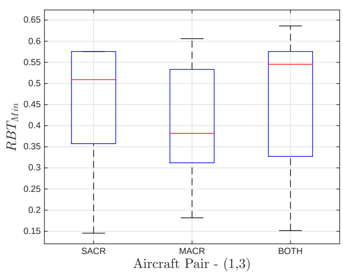
Figure G.7: Box plots of RBT_{min} for all the aircraft pairs, with the influence of forbidden zone.



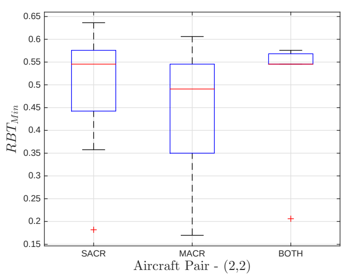
(a) (1,1)



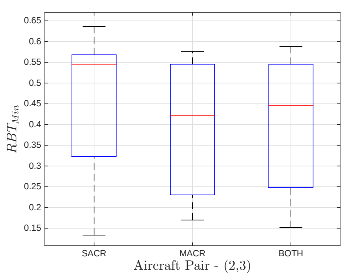
(b) (1,2)



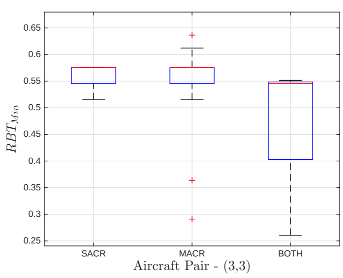
(c) RBT_{min} - (1,3)



(d) (2,2)



(e) (2,3)

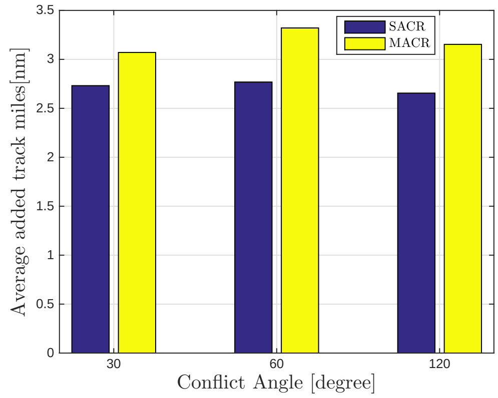


(f) (3,3)

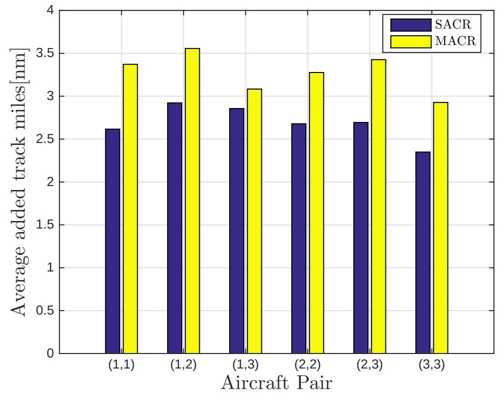
Figure G.8: Box plots of RBT_{min} - aircraft pairs, with the influence of forbidden zone.

G.3 Added Track Miles

In this section the added track miles [*nm*] with respect to conflict angles and aircraft pairs for all the experiment conditions are shown.

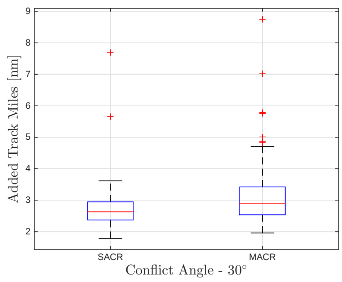


(a) Conflict angles

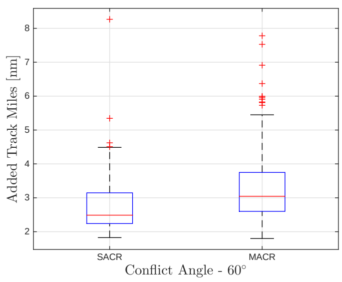


(b) Aircraft Pairs

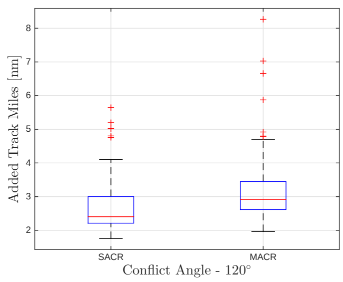
Figure G.9: Bar plots of Average track miles categorized by conflict angles and aircraft pairs.



(a) 30°

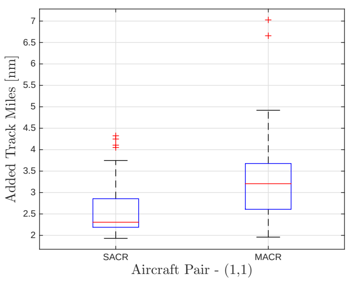


(b) 60°

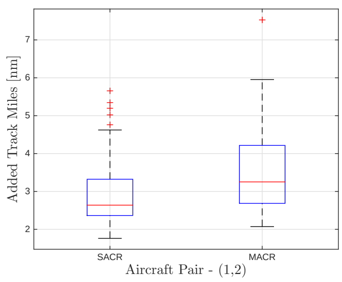


(c) 120°

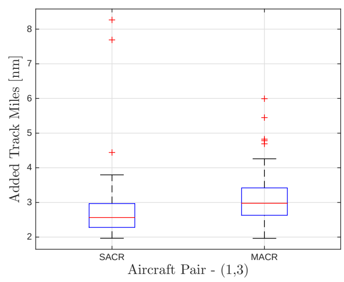
Figure G.10: Box plots of added track miles - conflict angles.



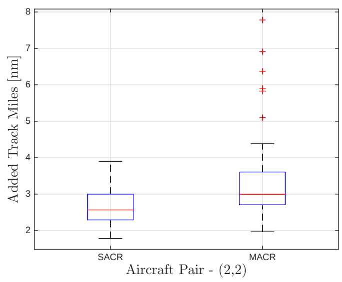
(a) (1,1)



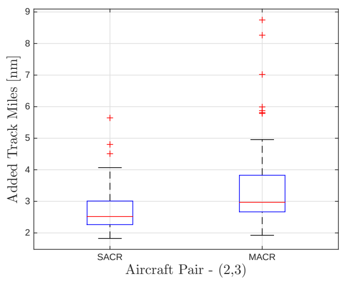
(b) (1,2)



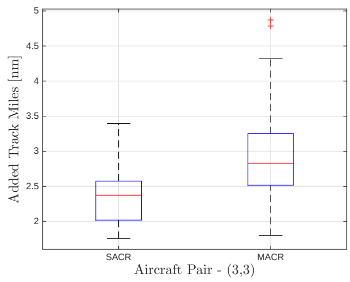
(c) (1,3)



(d) (2,2)



(e) (2,3)



(f) (3,3)

Figure G.11: Box plots of added track miles for all the aircraft pairs.

G.4 Workload

The box plot for the normalized ISA workload ratings is shown below.

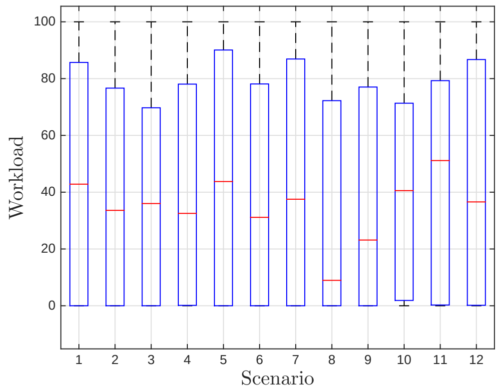
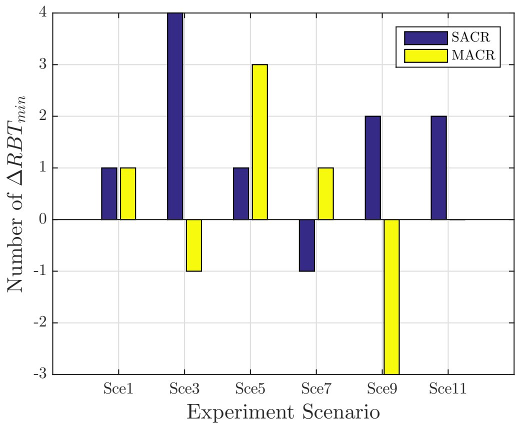


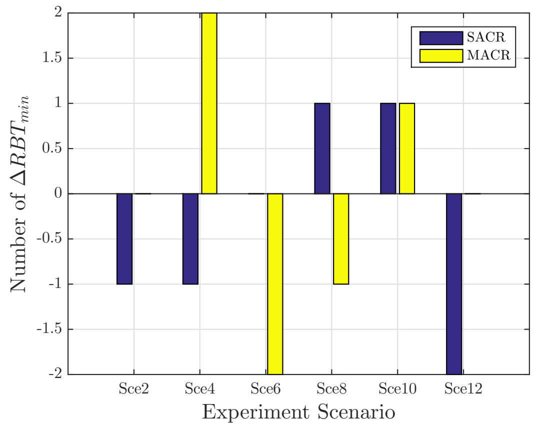
Figure G.12: Normalized ISA workload ratings for all the participants.

G.5 Positive and Negative Contributions of Robustness

The contributions of average ΔRBT_{min} for each participants is shown below.

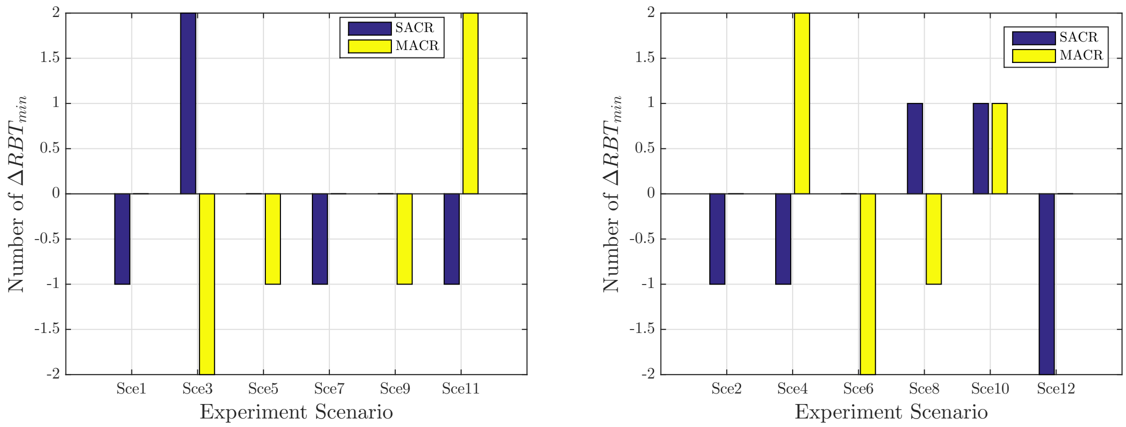


(a) Participant 1



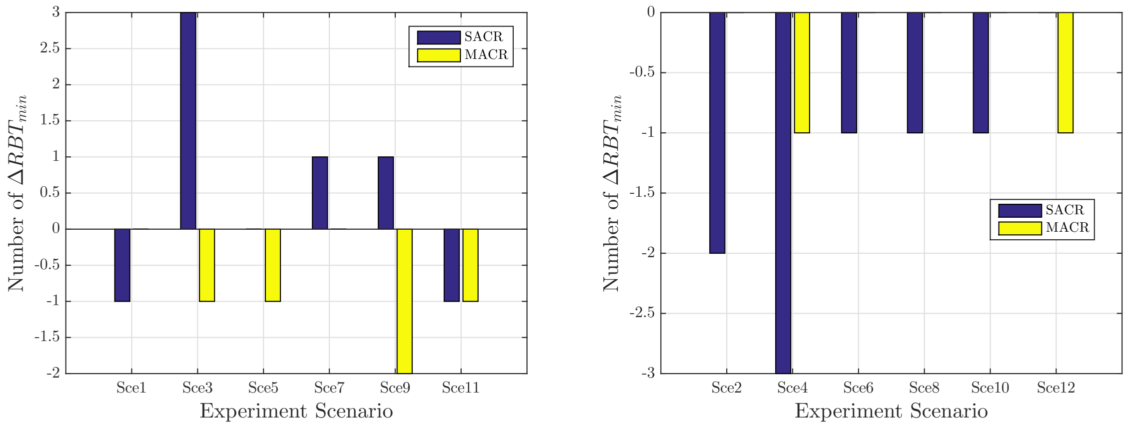
(b) Participant 2

Figure G.13: Bar plots of average ΔRBT_{min} for participants 1 and 2.



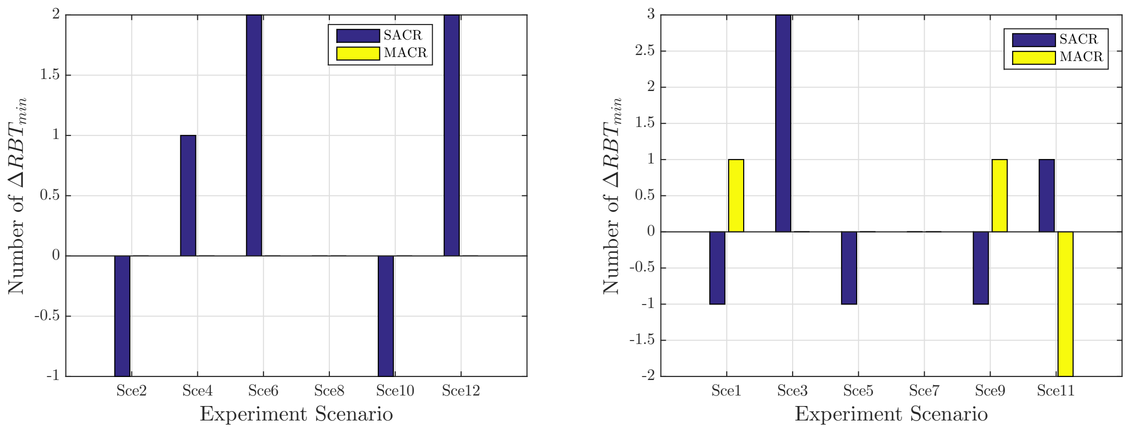
(a) Participant 3 (b) Participant 4

Figure G.14: Bar plots of average ΔRBT_{min} for participants 3 and 4.



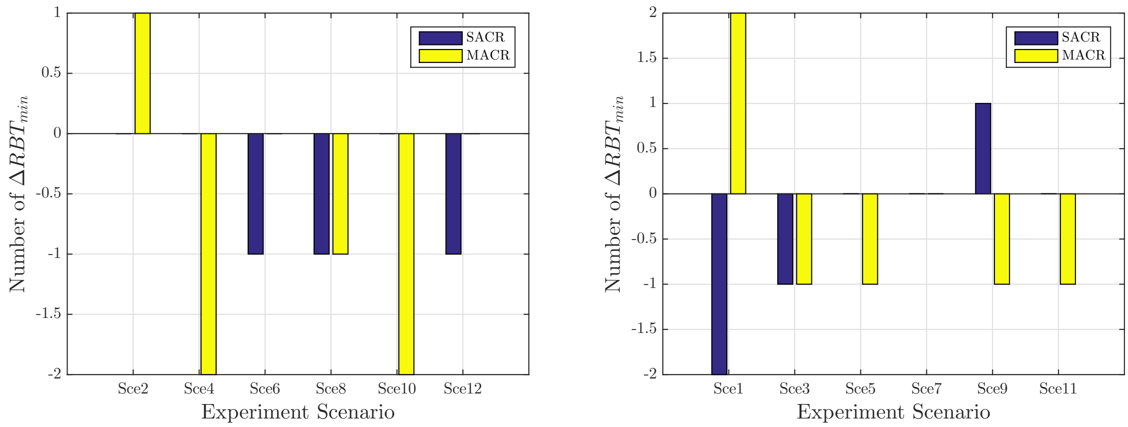
(a) Participant 5 (b) Participant 6

Figure G.15: Bar plots of average ΔRBT_{min} for participants 5 and 6.



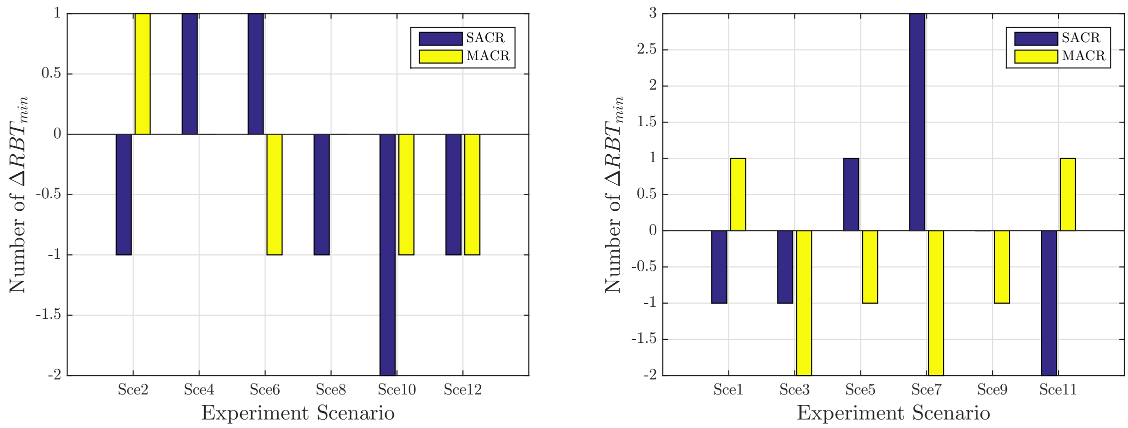
(a) Participant 7 (b) Participant 8

Figure G.16: Bar plots of average ΔRBT_{min} for participants 7 and 8.



(a) Participant 9 (b) Participant 10

Figure G.17: Bar plots of average ΔRBT_{min} for participants 9 and 10.



(a) Participant 11 (b) Participant 12

Figure G.18: Bar plots of average ΔRBT_{min} for participants 11 and 12.

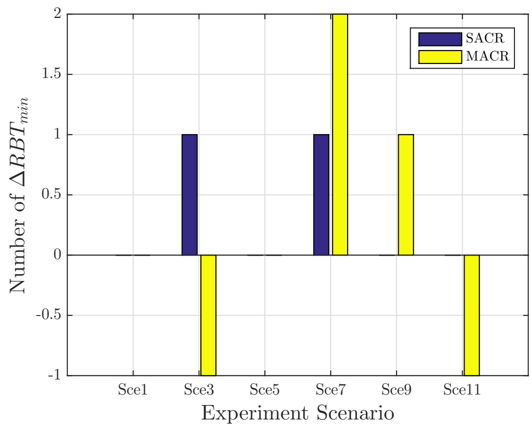


Figure G.19: Bar plots of average ΔRBT_{min} for participants 13.

G.6 Statistical Tests for Airspace Flexibility considering the influence of forbidden zone (no-go) area

A non-parametric test was conducted on the data of RBT_{min} values. A Friedman test was conducted for each of the six aircraft pairs, the results from the tests are described in Table G.1

Table G.1: Friedman Test Statistics^{a} for Robustness

Aircraft Pair	Total N	χ^2	df	p-value
AP1-(1,1)	**13**	**6.408**	**2**	**0.041**
AP2-(1,2)	**13**	**10.706**	**2**	**0.005**
AP3-(1,3)	13	2.735	2	0.255
AP4-(2,2)	13	3.360	2	0.186
AP5-(2,3)	13	5.760	2	0.056
AP6-(3,3)	13	3.00	2	0.223

It can be observed from the Friedman test statistics table (Table G.1) that the p-value is less than 0.05 for conditions AP1 and AP2 and the RBT_{min} values are significantly different in these conditions.

A post-hoc test was carried out with a Wilcoxon signed-rank test, where a comparison was made between the conflict angles. Since the number of pair-wise comparison here is 3 (i.e, k = 3), therefore the α value (Bonferroni correction of the significance threshold) is changed from 0.05 to 0.016.

Table G.2: Wilcoxon Signed Ranks test for robustness

AP1-(1,1)	Z	p-value
30° & 60°	-1.988	0.047
30° & 120°	-1.853	0.064
120° & 60°	**-2.412**	**0.016**
AP2-(1,2)	Z	p-value
30° & 60°	**-2.831**	**0.005**
30° & 120°	**-2.824**	**0.005**
120° & 60°	-1.363	0.173

The results from the Wilcoxon Signed Rank test for robustness value is shown in Table G.2. It can be noticed that the p-value is less than 0.016 for aircraft pairs AP1 and AP2. For AP1 the robustness value was significantly different for 60° conflict angle than 120° conflict angle. For AP2 the robustness value for 30° conflict angle was significantly different than 60° and 120° conflict angle.

H

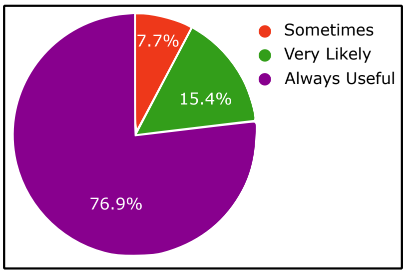
QUESTIONNAIRE RESULTS

Participants were asked to fill in an online questionnaire after all the experiment runs. In this following chapter along with the questions, the responses from all the thirteen participants are shown.

H.1 Online Questionnaire and Responses

Q1: How useful was the TSR in controlling traffic? Please explain.

COMMENTS:



101: without the TSR, I simply would not be able to control the scenarios without introducing conflicts.

102: Very useful. Sometimes the aircraft would get too close later on but I ended up trusting the software almost all the time.

103: I felt that conflict situations were never so complicated that TSR was required, and therefore solved most of them without.

104: I doubt whether this task would be feasible (4D!) without the TSR. Workload will be much higher for sure!

105: Allows for coming up with semi-optimal solutions to traffic conflicts and shows limitations imposed by other traffic. Although, not many conflict situations were encountered in the scenarios.

106: It gives clear insights in the options left. The fact that the size of the areas - red or green - shows you the solution space left is really intuitive.

107: Often confirms my strategies, sometimes causes me to reconsider.

108: it gives an insight in future conflicts and possible paths.

109: It helps visualize where you can or cannot steer an aircraft with respect to any future conflicts that might occur, which helps alleviate workload, as you do not have to extrapolate the aircraft path of other aircraft yourself.

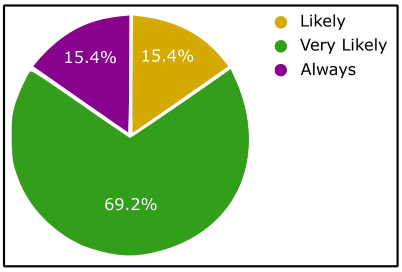
110: The TSR forced me to wait out traffic scenarios instead of making decisions as soon as traffic entered. If I had made the decisions right away, I might get in trouble later.

111: makes practically all resolutions "click & forget"

112: Allows for closer separation as you can clearly see the are of loss of separation.

113: Gives a clear overview of collision course (if any) and on the interference from aircraft in the vicinity.

Q2: Were you able to predict the evolution of traffic? Please explain. Comments:



101: with single aircraft commands, it was easier to understand where the aircraft would fly towards and to plan ahead. With multi-aircraft commands, it was more difficult to plan ahead (before the aircraft entered the sector) and I had to wait until all aircraft were in the sector to see how it would play out.

102: I would keep in mind that other aircraft are going to enter the sector. I would also try to predict the feasible TSR before they enter. I was wrong 60-70% of the time. Sometimes I would plan the waypoints placement away from the direction of aircraft which are about to enter to be able to have more feasible TSR region.

103: It did not take too long before I could see the traffic patterns, and that I could predict the solutions that the TSR would provide me with

104: Generally yes, I felt some anxiety some times when doing a 'multi' on two/more aircraft coming from different streams, as they merge to the same point, which means a conflict when TSR software fails, so you need to check (well I did check it while knowing that software was probably perfect in this experiment) to see if separation does not go too low. It never did, but still my workload was influenced by it (i.e., slightly higher).

105: Steady inflow of traffic and strategic routing make it easy to predict traffic evolution.

106: The appearance of conflict zones in the TSR gives insight in the effect of new aircraft entering the controlled area. After a few runs this helped predict what would happen when new traffic comes in.

107: There were a few times when I mis-estimated whether two aircraft would meet up, but most of the time my strategies worked out the way I thought they would.

108: conflict wise yes. how they will pass each other less, but that has more to do with experience.

109: The TSR does a lot of the work for you, but even for aircraft still outside of the sector I was able to see what would likely happen.

110: Mostly, as I could see traffic coming pretty far ahead of time.

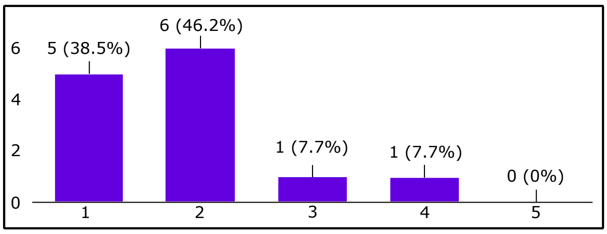
111: fairly low traffic level, easy to predict.

112: Yes, as the TSR confirmed the mental picture (routes)

113: Most of the times.

Q3: Were you surprised by any conflict which was not expected? Please explain.

Comments:



101: No, I anticipated all conflicts and would stick to my plan to bypass them all.

102: Yes very much. Especially when 2 aircraft have already entered and then a third aircraft enters right behind one of these 2 aircraft, I could not anticipate the behavior. In this case I would end up resolving the single aircraft first and then resolve the 2 aircraft which are behind each other separately. Some times the conflicts were created because of my placement as well, which I realized later on.

103: Sometimes I was more surprised that some solutions were possible, rather than being surprised that I observed conflicts.

104: I did not have any real loss of separation. When the aircraft turned red (conflict) I think that most of the times I saw it coming. I would say that I was never really surprised.

105: Due to the forbidden zone, aircraft that are still configured to fly through it impose restrictions that are not relevant, since they will have to be re-vectored.

106: Only once, when the conflict area of one of two conflicting aircraft was much larger than that of the other.

107: Not really. There were semi-unexpected conflicts, but in those situations I realized up front that it could go either way. It was, however, sometimes contrary to my maneuver decision.

108: not by any conflicts, just sometimes how close aircraft pass each other.

109: When aircraft enter the sector it is pretty obvious which ones are going to conflict. The TSR helps you predict any future conflicts, so there were no unexpected conflicts that occurred.

110: Once or twice an option I had thought of was not available (for example: two aircraft would arrive at the same point closer together than I expected), but as I had time to think I would have also thought of some alternatives.

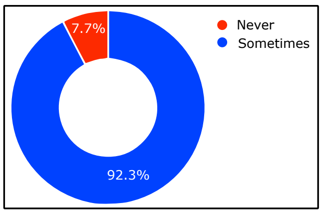
111: no unexpected conflicts.

112: Only when I wanted to merge traffic, from an angle of approx. 60 deg around the same way around the no-go zone.

113: Just once, when I had not selected an aircraft for multi-aircraft resolution. This was a surprise because I had thought I had selected it.

Q4: Did you forget to provide trajectory revisions to an aircraft, so that the aircraft would not fly through the no-fly zone/area? Please explain.

Comments:



101: All aircraft remained outside the no-fly zone.

102: In the training I did forget a lot of times. But my trainer was patient enough with me to tell me that I was forgetting to resolve it. By the end of the training it was clear and I never forgot to revise the trajectories in the actual scenarios. In one case, I did end up making the aircraft fly very close to the no-

fly zone which might not be feasible. I did have an
option to place second way point for the aircraft which was too close to the no-fly zone but I still let it be to avoid an additional waypoint.

103: -

104: No did not happen, but it did during training!

105: NA

106: No.

107: This never happened.

108: didn't happen

109: The overall workload was pretty low for me, so I had plenty of time to think about where to steer an aircraft.

110: This might happen if the scenarios were much more busy, but fortunately that was not the case.

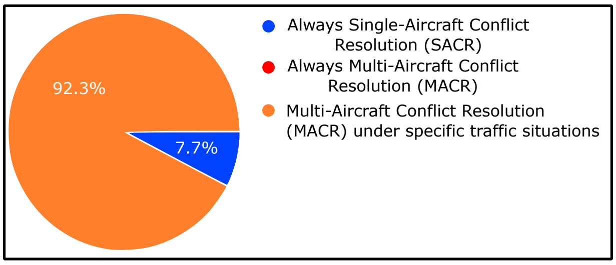
111: enough time for the task

112: No.

113: enough time for the task

Q5: Which resolution type would you prefer as a control action, Single-Aircraft conflict resolution (SACR) or Multi-Aircraft conflict resolution (MACR)? Please explain.

Comments:



101: I always preferred MACR for aircraft in the same stream IF they were close enough together. When aircraft in different streams were far apart, I would consider them separately (SACR). Thus, I used MACR for groups of aircraft within the same stream.

102: In 60-70% of the cases I would wait for the both aircraft to enter the sector and check their TSR and then decide if it would be better to use MACR or SACR. My initial instinct is to use MACR by analyzing the multi-aircraft TSR. But in 60-70% of the cases I was wrong about the feasible TSR for multi-aircraft. I would end up resolving them individually but not without checking multi-aircraft TSR first.

103: I feel that MACR can be used for solving more complicated conflicts, but SACR can be more fuel efficient.

104: I like the flexibility to choose the way to solve it. Some times the geometry asks for one solution over the other, although in this experiment the geometry was sort of easy (no go zone always in the center with the same distance to any of the entry points, so relatively easy to check the aircraft progress relative to the no go zone).

105: MACR for complex traffic conflicts, also useful for trailing aircraft

106: MACR is especially useful for aircraft coming from - more or less - the same direction.

107: For these scenarios I only used the combined travel space to check whether aircraft would have a problem together with the strategy I choose

108: multi aircraft is nice when aircraft quickly follow each other on the same line, otherwise single aircraft works fine

109: The MACR was useful, but I feel that it would be nicer if you could steer all aircraft along the same trajectory. With the current implementation of the MACR, when aircraft originate from the same direction, they all fly different trajectories to the created waypoint, after which they follow the same trajectory. It would be better if you could create the waypoint before the aircraft enter the sector and have them turn towards it upon entering. This way, all aircraft from the same direction will fly the same trajectory, which creates a more orderly pattern inside of the sector.

110: MACR makes aircraft in sequence or two columns of aircraft in sequence easier to control. Once it gets more busy or once I make a mistake, I would still need SACR to make some quick, agile adjustments.

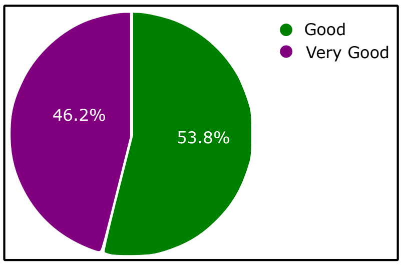
111: consider MACR only when traffic comes from more or less same direction

112: When aircraft are already lined-up, in this way the structure is kept and it is easier to anticipate

113: SACR is preferable if there are no other aircraft within the vicinity of the ownship. In any other case, MACR is preferred.

Q6: How will you rate your overall situational awareness during the experiment run? Please explain.

Comments:



101: Scenarios were not that difficult and I had sufficient time to plan my strategy before the aircraft entered the sector.

102: I was very much aware of the incoming aircrafts and how I would go about resolving them. But I would not be aware of the fact that later on even though the aircraft are not in conflict they would still get very close to each other.

103: Sometimes it was difficult to estimate which aircraft would enter the airspace earlier, but furthermore no problems.

104: Workload was relatively low, so enough time to check all aircraft and the situation. I expect that WL will increase with more traffic and more asymmetric no-go-zone situations/stream geometries. Then SA might not be high at all times as you may get 'tunnelled' into solving one conflict while at the same time something happens in another part of the sector.

105: Was aware of traffic and potential conflicts

106: The traffic density allowed for thorough understanding of the situation before conflicts occurred.

107: there was a lot of converging traffic, but an effective strategy was mostly apparent

108: awareness about conflicts was good, about paths slightly less (but that is due to lack of experience)

109: I felt that I was always in control and always resolved conflicts with the forbidden zone or other aircraft in a timely manner.

110: As I was able to predict traffic, I could also stay in control and well aware of what was going on.

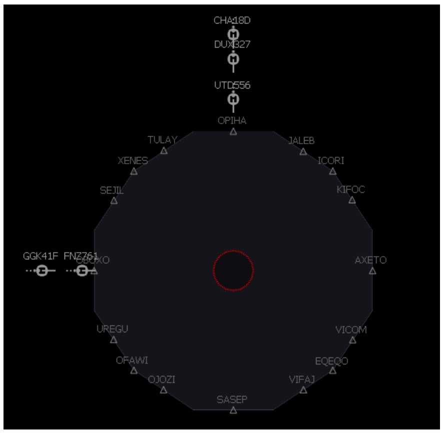
111: no problem with this traffic level

112: The difficulty was to the extent that full situational awareness was possible

113: I had a good situational awareness almost always.

Q7: How would you solve this traffic situation? Please indicate in your explanation the use of SACR and/or MACR clearances.

Comments:



101: I will do two MACR commands: one for the three aircraft entering from the top and one for the two aircraft entering from the left.

102: I would wait for the 2 aircraft on my left to enter the sector and resolve them using MACR by placing a waypoint below the no go area. Then I would wait for all the 3 aircraft on my top to enter the sector and resolve those 3 using MACR by the placing the waypoint to the left of no go area.

103: All SACR. GGK41F clockwise around the region, the rest counter-clockwise.

104: I see that we have 2 streams, where aircraft are pretty close within each stream. This suggests a 'multi'. In this case I would take the first aircraft from both streams and multi them, give them the same waypoint. Then wait until the second aircraft from both streams enter, and multi them as well, preferably to the same waypoint to maintain structure. Then do the third aircraft individually. AT ALL TIMES check whether there may be aircraft coming in from another direction, to see whether it may interfere with any of the solutions you 'see'.

105: MACR of the two aircraft from the west to the south of the zone, SACR of the first aircraft from the north to the east, MACR of the two remaining aircraft from the north to the east.

106: I would use SACR for the aircraft from the West and the first from the North. The second and third one coming in from the North I would handle using MACR.

107: SACR, all a/c counter-clockwise

108: Use MACR for the two aircraft entering from west, let them fly around south. Use MACR for the 3 aircraft from north, depending on the TSR either west (most likely) or east

109: I would issue a MACR clearance to a waypoint to the south of the forbidden zone to the aircraft coming from the west and a MACR clearance to a waypoint to the west of the forbidden zone to the aircraft coming from the north. As the two traffic flows are at an angle of 90 degrees, a MACR clearance for all 5 aircraft together would result in very large heading deviations, which is undesirable. When issuing the 2 MACR clearances, heading deviations are kept to a minimum.

110: I would send the first aircraft in each column over the bottom of the no-fly zone in a MACR. As soon as the second one enters I would also send it over the bottom. The last two coming from the top would go over the right if possible, otherwise over the left.

111: either have a/c go clockwise or anti-clockwise around area, zipper, first a/c east, SACR then ac north (S) then east + last two north (M) .

112: I would use MACR for the three ac from the north and two aircraft from the west and let one group pass behind the other

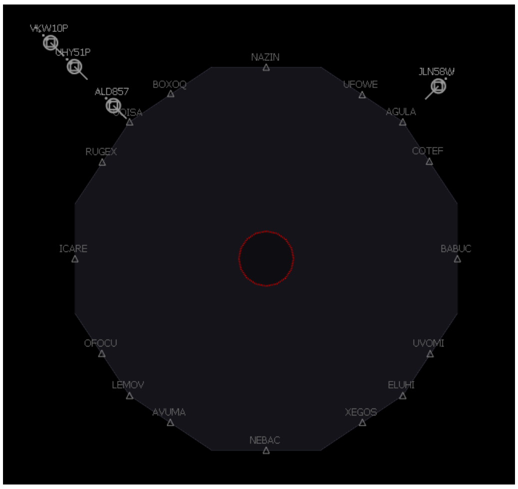
113: The 2 aircraft entering from the West will be resolved (MACR) first to go South of the no-go region. Then the 3 aircraft from North will be resolved (MACR) to go West of the go-go region. This way the aircraft from the North are following the 2 aircraft from the South near the no-go region.

Q8: How would you solve this traffic situation? Please indicate in your explanation the use of SACR and/or MACR clearances.

Comments:

101: I will do one MACR command and one SARC: one for the three aircraft entering from the top left and one SACR for the one aircraft entering from the top right.

102: I would wait for one aircraft to enter the sector from 2 different directions and then resolve them using MACR by placing the waypoint to the top left (north west) of no go area but not too far from it. And then wait for other 2 aircraft to enter the sector and resolve both of them by placing a waypoint to the top right (north east) of the no go area but not too far from it.



103: Use MACR to solve the first conflict- if no efficient solutions are found then go back to SACR. The last two aircraft to enter the airspace follow the route of ALD857

104: I would multi the first aircraft in the stream with the N/E a/c when they have entered the sector. Then multi the other two remaining aircraft from the N/W stream, preferably to the same waypoint if possible. Again always check whether a/c are coming from other directions.

105: SACR of the first aircraft from the north-west to the south-west, SACR of the aircraft from the north-east to the north-west, MACR of the two remaining aircraft from the north-west to the south-west.

106: Same here, the second and third from the North-East I would handle using MACR, the other two aircraft using SACR.

107: SACR, all a/c clockwise

108: first use macr on the three aircraft coming from northwest, let them go around west. Then SACR on the aircraft from northeast and depending on TSR, probably west as well

109: I would issue a MACR clearance to a waypoint to the south-west of the forbidden zone to the aircraft coming from the north-west and a MACR clearance to a waypoint to the north-west of the forbidden zone to the aircraft coming from the north-east. As the two traffic flows are at an angle of 90 degrees, a MACR clearance for all 5 aircraft together would result in very large heading deviations, which is undesirable. When issuing the 2 MACR clearances, heading deviations are kept to a minimum.

110: I would send the first of the column coming from top-left and the lone aircraft from the top-right together in MACR underneath the no-fly zone. Then the two remaining aircraft from the top-left together in a MACR over the top or bottom of the no-fly zone, depending on which is possible and other incoming traffic.

111: route ac 1 nw (S), prob clockwise, use SACR on ac ne to determine which way to route, waiting on second from nw. then route remaining two nw with MACR

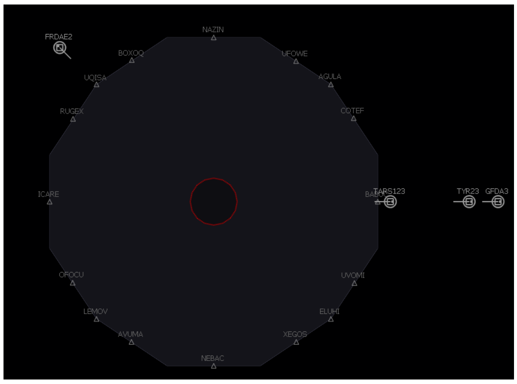
112: Use MACR for the three aircraft coming from the north west and try to either fit the one aircraft between the first two or let it pass behind the three ac.

113: The aircraft entering from the North-West will be resolved (SACR) first to go South-East of the no-go region. Then the 3 aircraft from North-West will be resolved (MACR) to go North-West of the go-go region. This way the aircraft from the North-East are following the aircraft from the North-East near the no-go region.

Q9: How would you solve this traffic situation? Please indicate in your explanation the use of SACR and/or MACR clearances.

Comments:

101: I will do two SACRs and one MACR: one SACR for the aircraft entering top-left and one SACR for the lone cowboy entering from the right. Then, one MACR for the two aircraft entering from the right. I will also re-route the three aircraft entering from the right along the same intermediate waypoint location to build a nice structure.



102: From my experience with the scenarios, I think I would resolve the aircraft entering from the right using SACR by placing the waypoint below the no go area. Then resolve the aircraft coming from north west using SACR by placing the waypoint to the NE of the no go area but not too far from it. Finally resolve the 2 aircraft coming from right by making it closely follow the leading aircraft.

103: all aircraft fly counterclockwise around the region. Just use SACR for efficiency

104: You see that the first a/c on the east comes in first and that then the other two E aircraft will interfere with the N/W a/c/ You can see that because the sector is symmetric and the nogo zone is in the center. Because all a/c have the same speeds the time to conflict is just distance. So what I would do is individually lead the first E a/c. Then wait until the other 2 E a/c and the 1 N/W a/c have entered and give them a multi.

105: SACR of the first aircraft from the east to the south-west, SACR of the aircraft from the north-west to the north-east, MACR of the two remaining aircraft from the east to the south-west.

106: Same as well. The cluster of two from the East I would handle using MACR.

107: SACR, all a/c counter-clockwise

108: First SACR on the aircraft from the east, let it fly around south. Them SACR again on the aircraft from northwest, go around west. Then MACR on the two aircraft coming from the east and depending on TSR choose a direction

109: I would issue a MACR clearance to a waypoint to the north-east of the forbidden zone to the aircraft coming from the north-west and the first aircraft coming from the east. I would then issue a MACR clearance to a waypoint to the south of the forbidden zone to the other aircraft coming from the east. A MACR clearance could be given to all three aircraft coming from the east and then a SACR to the aircraft coming from the north-east, but the aircraft coming from the east might be slightly too far apart for this. The MACR clearance given to the 2 aircraft coming from the east is given in the other direction than the clearance for the first aircraft from the east, as I think the 2 aircraft from the east would create a conflict with the aircraft coming from the north-west if steered in the same direction as the first aircraft coming from the east.

110: I would send the aircraft from the top-left and from the right in a MACR past the bottom of the no-fly zone. Then the last two from the right over the bottom or top in an MACR, depending on possibilities and other oncoming traffic.

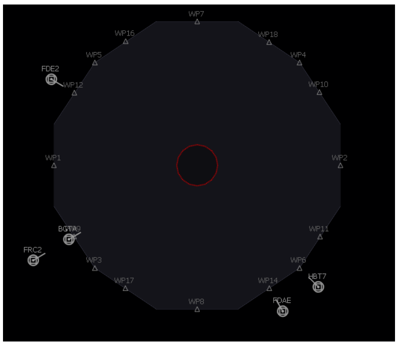
111: route ac e north from area, then ac nw south (S), then remaining two east using MACR, north again

112: Let the first aircraft from the east go to the south of the no-go and the aircraft from the north west to the north of the no-go zone and use MACR to divert the two from the east to either north or south depending on the situation

113: The first aircraft entering from the East and the aircraft entering from the North-East will be resolved (MACR) to a waypoint to the South-West of the no-go region. This provides more space for the 2 aircraft following in the east. These will be resolved (MACR) to a waypoint to the North of the no-go region.

Q10: How would you solve this traffic situation? Please indicate in your explanation the use of SACR and/or MACR clearances.

Comments:



101: I will do one SACR (top-left aircraft), one MACR for aircraft entering bottom-left and one MACR for aircraft entering bottom-right. The two aircraft bottom right have a shallow conflict angle and I would consider them approx. in the same stream.

102: Wait for BGTA, FDAE, HBT7 and FDE2 to enter the sector. Check the multi aircraft TSR. Resolve the BGTA using SACR by placing way point above the no go area and resolve FDAE and HBT7 together using MACR where ever its possible. The FDE2 would then be resolved using SACR and then finally FRC2 using SACR but waypoint placement can only be decided by seeing the TSR.

103: first aircraft clockwise, the combination of FDAE and HBT7 solved with MACR, the FDE2 and FRC2 with SACR

104: I would try to create a round about around the nogo zone. You see that basically all a/c will enter the sector at the same time, their distance to the center is approx. the same. I would separate them and avoid the nogo zone by creating the roundabout such that all a/c will go in a counterclockwise direction around the nogo zone. So, the two a/c from the SE get a multi to a joint waypoint E of the nogozone. The a/c from S/W and N/W get a multi to a joint waypoint S of the nogo zone. Then wait for the fifth a/c coming from S/W and put it to the same waypoint S of the nogo zone. If possible.

105: SACR of the first aircraft from the south-west to the south-east, MACR of the two aircraft from the south-east to the north-east, SACR of the aircraft from the north-west to the south-west, SACR of the remaining aircraft from the south-west to the south-east.

106: Use MACR for the two aircraft coming in from the South-East. I would handle the other three separately using SACR.

107: the two a/c to the S-E together with MACR counter clockwise. The other three with MACR also CC

108: Use MACR on the two aircraft coming from SSE and SE, let them go around east. Then check the TSR for FDE2, probably reroute it SACR around east as well. Finally MACR once the second aircraft from the southwest has entered and redirect them west

109: I would give a MACR clearance to a waypoint to the north-east of the forbidden zone to the 2 aircraft coming from the south-east, a MACR clearance to a waypoint to the south-east of the forbidden zone to the 2 aircraft coming from the south-west and a SACR clearance to a waypoint to the south-west of the forbidden zone to the aircraft coming from the north-west. In this way, an orderly pattern is created around the forbidden zone, ensuring that no conflicts will occur.

110: First of all I would watch out not to do a MACR with aircraft that are headed in a (roughly) head-on collision course, so coming from opposite directions. Probably I would try to use an MACR for the two aircraft coming from the bottom right to send them over the no-fly zone with some buffer. Then I would direct the aircraft from the bottom left and top left in a MACR to travel underneath the no-fly zone. What I would do with the final aircraft from the bottom left depends on what possibilities I see in its SACR.

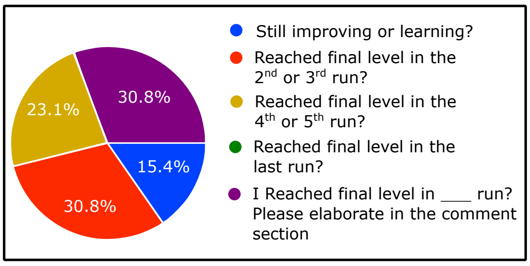
111: ac from sw north of area, (S), then two from se MACR south of area, acr nw north of area, remaining ac sw south of area

112: Use MACR to let the two aircraft from the south east pass the no-go to the east, use MACR to let the two aircraft from the south west pass the no-go to the west and let the single aircraft pass behind the latter two

113: The no-go region can be used like a round about. The 2 aircraft from the South-West will be given a way point (MACR) South-East of the no-go region. The lower aircraft from South-East will be given a waypoint South-East of the no-go region (SACR). The upper aircraft from the same direction will also be given a waypoint on the South-East side, but a little radially outwards from the no-go region (SACR). The aircraft from the North-West will be given a waypoint to the South-West of the no-go region (SACR).

Q11: What is your impression about the learning curve during the overall experiment runs?

Comments:



101: After two or three runs I noticed that I recognized the same scenario parts and I learned from earlier mistakes.

102: The learning curve gets better with each scenario and training also helps but I feel I can still improve a lot.

103: Somewhere around this runs, I noticed that I could predict the results that I expected from the MACR

104: This includes the training runs! I think I got it after training #5 or 6. However, I think that when the scenarios would be more complicated, with different geometries and locations of the no-go zones, then I would still be adapting the way I use the tools available, find better strategies for more difficult situations. For this experiment, with the current level of complexity, I think I have learned the trick before the measurements phase.

105: I reached the final level in the first run.

106: I reached the final level in the second run.

107: I had a consistent strategy from the end of the first run onwards

108: during the training sessions I was still having a huge learning curve, but once the actual runs started, I was aware of all the options

109: I feel that I reached the final level of learning during the training sessions already.

110: By 2nd run

111: for this level of traffic, reached final perf level already in training

112: -

113: N/A

Q12: Please mention here the things which you would suggest to be changed about the Travel Space Representation (TSR). Please explain.

Comments:

101: Perhaps including the red areas of the aircraft that are still outside the sector, because it could make my planning perhaps more efficient (quicker), but perhaps also makes me more lazy and not encourage me to start making my own plan. Now I felt very much engaged in the planning.

102: The aircraft passing through the no go area can be highlighted only within the no go region. Also it would be better to use a square monitor such that the areas around the sector (display area) are symmetric from each side. Top and bottom are smaller then the left and right side.

103: Also indicate which locations of solutions are not available due to the forbidden regions.

104: Nothing, the TSR is very good. My main advice would be on the MACR. When working with multiple aircraft coming from the same stream, it is perfect. These aircraft (on the same stream) are separated and when they fly the same speed will remain separated when you merge them to the same point. They will simply arrive later in time, easily monitored and no extra work. However, when working with multiple aircraft from different streams I do not really like the fact that these aircraft will be merging to the same point. Here the software will check whether they arrive that point at different times to keep separation, but sometimes the aircraft get quite close (depending on your choice for the waypoint of course) and are on a 'conflict' course most of the time. This means that, in order to keep things safe, and thinking about possible glitches in the software, you HAVE to keep your attention to them, especially when they are close. So I would suggest to have TWO waypoints (when you work with two a/c coming from different streams) that are closely located but that will not only separate the aircraft in TIME but also in POSITION.

105: For MACR ability to include aircraft outside the sector. Inclusion of forbidden zone limitations. Extension to include altitude, uncertainties due to weather (wind) or aircraft performance model inaccuracies.

106: No suggestions, I like the concept.

107: I would change the mapping of the buttons. No multi-a/c selection without a key modifier. perhaps also an area-selection possibility (drag area w. mouse)

108: -

109: Nothing, I like it the way it is now.

110: Allow the pressing of Ctrl to select multiple aircraft (not hard requirement, simply might be useful for intuitiveness). There are some scenarios which would be more difficult to solve, as the last one presented in this questionnaire, in which I think that first you would have to induce a conflict and later resolve it. Having some way to gain insights into this process would be useful, as now during the training run I had to resort to some inefficient SACR maneuvers to solve the scenario.

111: already in de-briefing

112: Include no-go zone, maybe show in a way the trend of the red zone (eg. shifting to the left/right)

113: The go region is all green. An indication of a mathematically favored region by having various shades of green might aid the controller in taking more optimal decisions to resolve conflicts.

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