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Exploring the Potential Benefits of Multi-Aircraft Trajectory Manipulation in Future Air Traffic Control

R. Nagaraj, R. E. Klomp, C. Borst, M. M. van Paassen and Max Mulder

Abstract—Future Air Traffic Management is expected to shift towards four dimensional trajectory (4DT) management, requiring new decision support tools for air traffic controllers to meet stringent time and position constraints. In previous work, a prototype human-machine interface has been developed for 4D trajectory manipulations of single aircraft. This paper describes a tool for *multi-aircraft* manipulation and investigates its potential control efficiency benefits. A human-in-the-loop experiment ($N = 13$) has been conducted using scenarios with sector disruptions and varying conflict geometry. Results show that participants preferred to use multi-aircraft manipulation for groups of aircraft having small convergence angles. Since the current implementation involves re-routing all selected aircraft through one common waypoint (referred to as a ‘merge point’), extra additional track miles were flown and airspace robustness reduces. Regarding efficiency and safety, multi-aircraft trajectory manipulation seems favourable only for smaller convergence angles, although this also depends on the way the operators place the aircraft merging points. For future development, attention should be devoted to making flight efficiency constraints of each aircraft more salient, enabling controllers to better time the rerouting multiple aircraft and more fairly distribute re-routing costs.

I. INTRODUCTION

Trajectory Based Operations (TBO) is a concept proposed by the Next Generation Air Transportation System (NextGen) and Single European Sky ATM Research (SESAR) [1], [2]. The concept hinges on making aircraft adhere to stringent position and time constraints to keep aircraft safely separated whilst increasing airspace capacity. Unexpected separation provisions and delays could, however, disrupt the tight planning schedule and would thus create a need for short-term perturbation management [3].

To support controllers in managing such perturbations, Klomp *et al.* [4] designed and evaluated a human-machine interface that implemented a so-called “travel space representation” concept, inspired by Ecological Interface Design principles [5]. In that concept, when a controller selects an aircraft, the boundaries for safe and feasible control actions for that aircraft are computed by automation and shown in real-time. The controller can then directly manipulate the 4D trajectory of that aircraft, adhering to all space and time constraints, creating safe, efficient and conflict free solutions to unexpected traffic perturbations. Although initial experiments were promising in terms of achieved control performance and safety, flight efficiency in terms of additional flown track miles was not equally and fairly distributed among aircraft. Given that the future air traffic

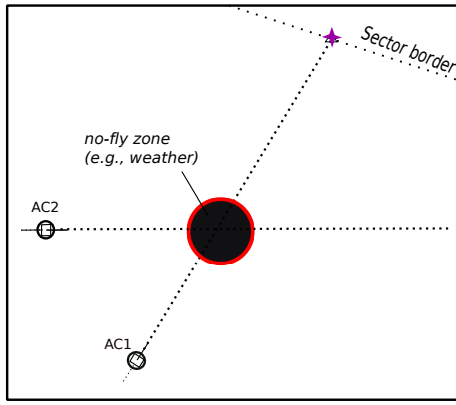
management (ATM) system focuses on cooperative ATM [6], [7], sharing the costs of a re-route would be preferable [8].

In this paper, the potential flight performance and additional safety benefits of multiple-aircraft trajectory manipulation and conflict resolution (MACR) are explored and compared to single-aircraft trajectory manipulation conflict resolution (SACR). These concepts will be described in detail in Section II. A human-in-the-loop experiment, described in Section III, was done in which participants could use both SACR and MACR control actions to resolve traffic conflicts and sector disruptions. Experimental results are discussed in Section V. The paper ends with conclusions and recommendations in Section VI.

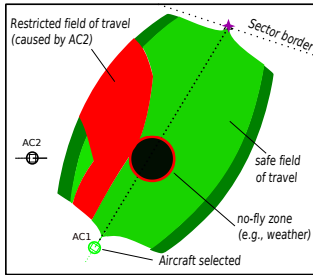
II. SINGLE VS MULTI-AIRCRAFT TRAJECTORY MANIPULATION AND CONFLICT RESOLUTION

To understand the difference between single- and multi-aircraft conflict resolution, consider the traffic situation as shown in Figure 1(a). The situation depicts two aircraft that are planned to leave the sector at the specific sector exit waypoint at a specific time. However, they both will also cross through a no-fly zone, representing for example a weather cell, requiring controller actions to re-route both aircraft to avoid crossing the no-fly zone, whilst meeting the original planned sector exit position and time.

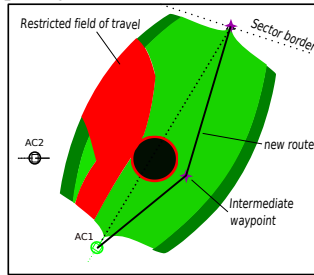
With the solution-space interface developed in previous research, also known as the Travel Space Representation (TSR), the controller needs to select each aircraft individually to re-route them. Selecting an aircraft will open the travel space visualization for that selected aircraft, see Figure 1(b). This visualization represents the collection of all intermediate re-routing waypoints that respect both the aircraft performance boundaries (e.g., the speed envelope) and the metering constraints at the sector exit. Automation algorithms compute these boundaries for all possible places where controllers can add an intermediate waypoint and show the feasibility in real-time on the display. Additionally, parts of the solution space can be blocked by other aircraft and/or a no-fly zone, limiting the available options for placing intermediate waypoints. For example, placing an intermediate waypoint in the red area indicated in Figure 1(b) will result in a loss of separation with the other aircraft. Placing an intermediate waypoint outside of the solution space boundary will result in a delay at the metering fix, because the aircraft cannot fly faster than its maximum speed. In Figure 1(c), one possible solution for AC1 is illustrated where a controller placed an intermediate waypoint outside the red conflict zone and no-fly zone. For



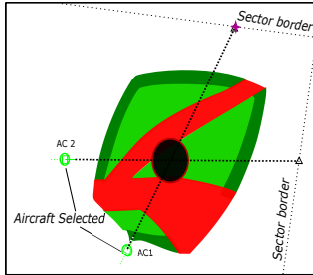
(a) Two aircraft requiring a re-route



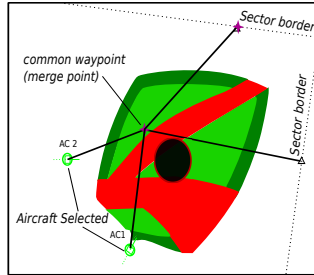
(b) Solution space for the selected aircraft AC1



(c) New trajectory for the selected aircraft AC1



(d) Combined solution space for selected aircraft AC1 & AC2



(e) New trajectories for selected aircraft AC1 & AC2

Fig. 1: Two-aircraft traffic conflict (top); Single (middle) versus multi-aircraft (bottom) trajectory management and conflict resolution.

the other aircraft (AC2), the controller would need to perform similar actions.

With the new multi-aircraft trajectory manipulation capability, selecting multiple aircraft creates the *combined* solution space for those aircraft. In its most succinct form, this combined solution space portrays the intersection where the solution-space shapes of all selected aircraft overlap, see Figure 1(d). Placing an intermediate waypoint outside the red areas and no-fly zone will now create a *common merge point* for all selected aircraft from which they will diverge again to leave the sector at their own exit waypoint and original exit times, see Figure 1(e).

In terms of control efficiency, the multi-aircraft re-routing capability requires fewer controller actions. That is, for re-routing two aircraft using SACR, six actions are required (i.e., selecting, proposing, and implementing multiplied by

the number of aircraft), whereas for MACR only four actions are needed (i.e., selecting the involved aircraft, propose and implement). For ten aircraft, SACR would require 30 actions and MACR 12 actions. Thus for large numbers of aircraft, the required control actions for MACR will result in lower physical controller workload compared to SACR.

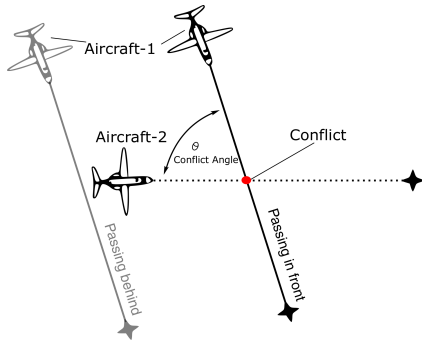
In terms of flight efficiency and safety, the benefits of MACR versus SACR can vary, however. Using a small-scale batch study, featuring two aircraft flying at the same speeds in a symmetrical crossing conflict situation (see Figure 2), different suitable locations for intermediate waypoints as a function of traffic convergence angles were explored and quantified in terms of resulting additional flown track miles and minimum values of the achieved airspace robustness. Here, robustness is identified as the relative size of the available travel space (expressed as the ratio of the “green” area over the total (“green plus red”) area) after the re-route has been implemented.

For this batch study, instead of changing the time of entry of the second aircraft, the new intermediate waypoint was placed on the edge of the minimum separation standard of 5 NM by using SACR and then by MACR to resolve the conflict, see Figure 2. Here, T_b is the trajectory when Aircraft-2 passes *behind* Aircraft-1; T_f is the trajectory when it passes *in front* of Aircraft-1.

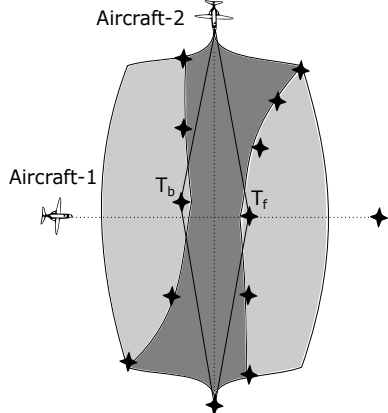
Results of the analysis are shown in Figure 3. In terms of additional track miles, it can be observed in Figure 3(a) that at low conflict angles, the differences between SACR and MACR are small. This makes sense, because at small conflict angles, aircraft will be flying almost behind each other, resulting in a combined solution space that will be almost the same as the shape of one solution space, and thus the MACR, will result in the same solution options as SACR. At higher conflict angles, however, MACR will be at a disadvantage compared to SACR, because the merge point will make both aircraft fly longer distances. With SACR, only one aircraft will be affected in terms of flying more track miles.

In terms of minimum robustness, from Figure 3(b) and Figure 3(c) it can be observed that the location of the intermediate waypoint plays an important role. For SACR, the impact of the waypoint locations on robustness is rather small. For MACR, however, merging waypoints placed at locations that will make aircraft fly almost head-on toward that merge point will result in much lower robustness. For example, merge point location 1 shown in Figure 2(c) will result in the lowest minimum RBT value in Figure 3(c) for the 90 degrees conflict angle. Placing merge points where traffic will be flying more behind each other, robustness values will be larger. At higher conflict angles, the difference between SACR and MACR will be similar as the options to place ‘head-on’ merge points are not present anymore.

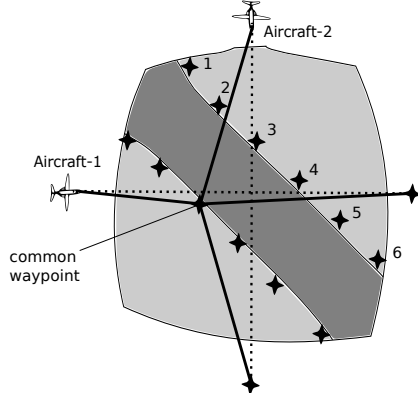
To conclude, whereas MACR seems favourable in terms of reduced physical workload, average additional track miles and higher achieved minimum robustness values at low conflict angles, it does matter where to place the merge waypoints. Thus, for large traffic crossing angles, it would



(a) Definition of the conflict angle



(b) Explored waypoint locations for SACR (90 [deg])



(c) Explored waypoint locations for MACR (90 [deg])

Fig. 2: Single- and multi-aircraft solution spaces for the 90° conflict angle situation including the explored intermediate waypoint locations for both SACR and MACR.

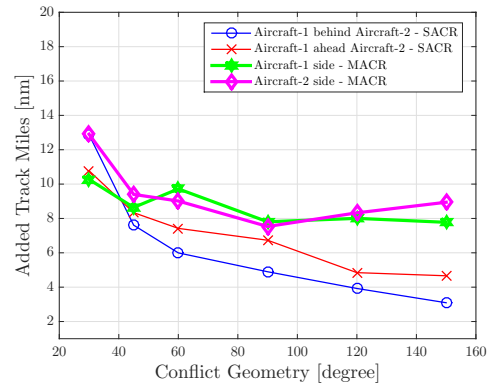
be better to revert to SACR to resolve conflicts.

III. EXPLORATORY EXPERIMENT

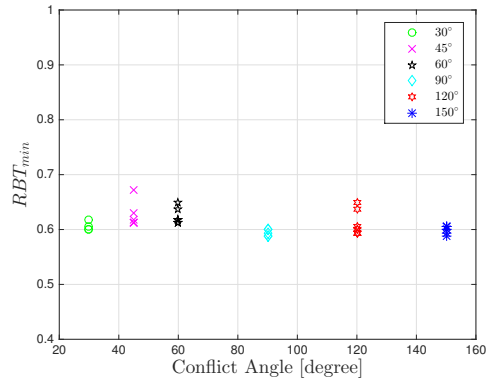
To investigate how and when participants would use the multi-aircraft solution space to resolve airspace perturbations, an exploratory experiment was performed.

A. Participants & Instructions

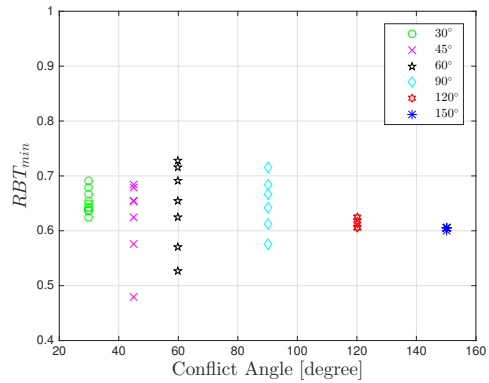
Thirteen participants (2 females and 11 males with an average age of 30 years) took part in the experiment. All participants had prior experience and knowledge of ATC and the previous interface for 4D trajectory management in which



(a) Average additional track miles



(b) Minimum robustness (RBT_{min}) for Aircraft-1 passing behind Aircraft-2 (SACR)



(c) Minimum robustness (RBT_{min}) for Aircraft-1 passing behind Aircraft-2 (MACR)

Fig. 3: Total additional track miles and minimum robustness for SACR and MACR scenarios involving two aircraft, shown for a set of different conflict geometry angles.

they could only perform SACR actions. The participants' main control tasks for this experiment were to: (1) maintain a safe separation of five nautical miles (5 NM) between aircraft at all times, and (2) to reroute all aircraft whose trajectories intersected a no-fly zone, while making sure to minimize the path deviation and the number of control actions. The participants could use both SACR or MACR clearances for re-routing; only horizontal trajectory changes could be made.

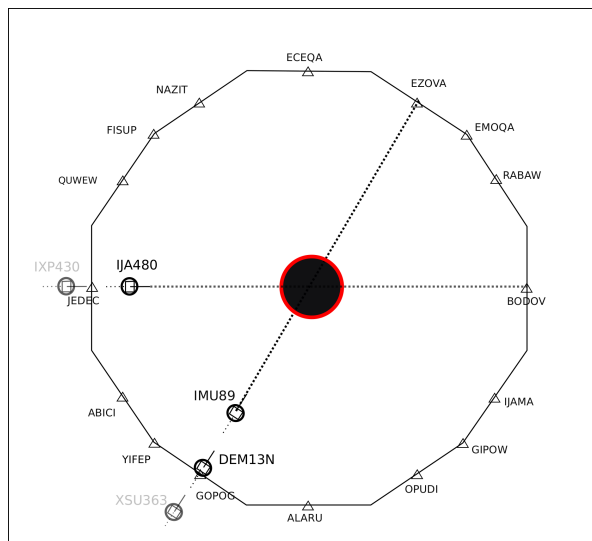


Fig. 4: Airspace sector to be controlled.

B. Traffic Scenarios

Participants needed to reroute aircraft in a fixed hypothetical en-route airspace sector with a width and height of 140 NM, see (Figure 4). Each traffic scenario featured a circular “no-go” area at the center with a radius of 10 NM, which required participants to re-route aircraft. The number of waypoints in the airspace was fixed, but the names of the waypoints were changed for each experiment run, in order to eliminate confounds due to scenario recognition. All aircraft were Airbus A320 flying at flight level FL290.

The variations in the scenarios were created by manipulating the traffic crossing angles at 30, 60 and 90 degrees in addition to manipulating how many aircraft pairs would enter the sector within the same time period. Given the sector layout and the entry/exit waypoint locations, three traffic crossing angles could be created. In total, six aircraft pairing types were defined that were varied over the three crossing angles, resulting in a total of ($3 \times 6 =$) 18 experiment conditions. In Figure 5 all six aircraft pairing types for the 30-degree conflict angle can be seen.

The combinations of crossing angles and pairing types were encoded in a set of six trial scenarios as indicated in Table I. Each scenario featured a particular sequence of crossing angles and pairing types, interspersed with short ‘rest’ periods before the next pairing type would enter the sector. These rest period were created to ensure that the rerouting options for the next pairing type were not affected by how controllers rerouted the previous pairing type. The trial time per scenario was 60 minutes, but to prevent boredom, the simulator ran at four times fast forward speed, which made each scenario last 15 minutes. All participants needed to control all scenarios, albeit in a different order.

Finally, within each scenario the participants could only reroute the aircraft when they were inside the sector. They could, however, always see the aircraft entering the sector, such that they could anticipate on the number of aircraft

TABLE I: Distribution of crossing angles (CA) and aircraft pairing (AP) types within each trial scenario.

	Condition A		Condition B		Condition C	
	CA	AP	CA	AP	CA	AP
Scenario 1	60	2,3	30	1,1	120	1,2
Scenario 2	30	1,3	120	2,3	60	1,1
Scenario 3	CA	AP	CA	AP	CA	AP
	120	3,3	60	1,2	30	2,2
Scenario 4	CA	AP	CA	AP	CA	AP
	60	2,2	120	1,1	30	1,2
Scenario 5	CA	AP	CA	AP	CA	AP
	30	2,3	60	3,3	120	1,3
Scenario 6	CA	AP	CA	AP	CA	AP
	120	2,2	30	3,3	60	1,3
<i>time [min]</i>	<i>10</i>	<i>15</i>	<i>10</i>	<i>15</i>	<i>10</i>	<i>10</i>

that needed to be rerouted. Given that not all aircraft with a pairing type entered the sector at the exact same time, it was left to the participant to decide to either control each aircraft individually (i.e., SACR) as soon as one entered the sector, or wait until more (or all) aircraft within a pairing type were inside the sector such that they could be rerouted simultaneously (i.e., MACR).

C. Dependent measures

To measure the control efficiency and resulting flight efficiency and safety in how participants resolved the scenarios, the following dependent measures were defined:

- Number of no-fly zone intrusions;
- Number of losses of separation (protected zone intrusions);
- Number of SACR and MACR clearances. In case MACR clearances were provided, a division was made into rerouting multiple aircraft within the same traffic stream (Same-Stream) or rerouting multiple aircraft between two traffic streams (Inter-Stream), see Figure 6;
- Average additional flown track miles per aircraft in nautical miles; and
- Minimum robustness contribution per control action taken by each participant.

Note that given the low traffic count and relatively long scenario runtime, measuring the experienced workload was considered to be of limited importance for this experiment and hence was not measured.

IV. RESULTS

In none of the trials, losses of separations or no-fly zone incursions were recorded. In Figure 7, the number and type of clearances, categorized by traffic conflict angles and aircraft pairs, are shown. From this figure, it can be observed that participants preferred SACR at larger conflict angles, which from perspective of limiting additional track miles is also favourable. More MACR actions were done for pairing types featuring more aircraft. Interestingly, however, the (2,3) type was mostly solved by SACR actions. This is mainly caused by the relatively large separation distance between the aircraft in this pairing type (see Figure 5). That is, participants needed to wait relatively long before all aircraft

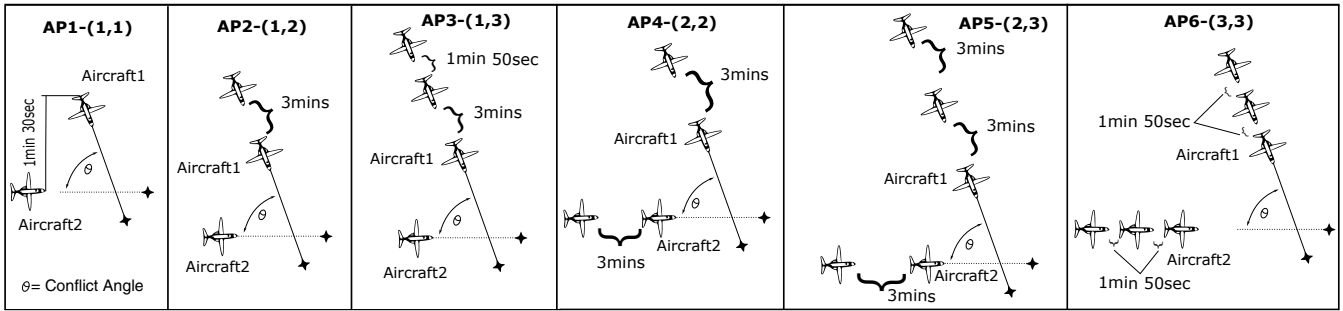


Fig. 5: Scenario design of all six aircraft pairs for 30° conflict angle.

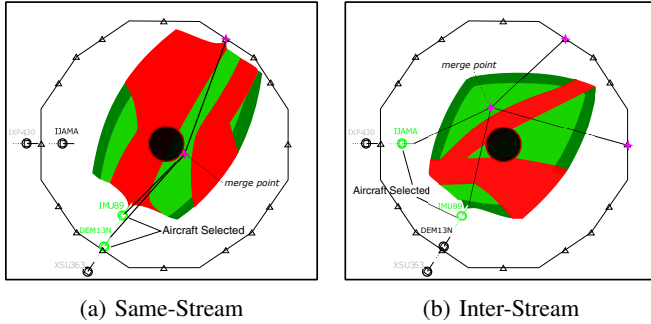


Fig. 6: Definition of Same-Stream and Inter-Stream MACR commands.

were inside the sector before a MACR action could be given. Hence, they mostly opted for quicker SACR actions instead.

The way participants used the MACR feature was mostly as expected: in the majority of situations, they used MACR for aircraft within the same traffic streams, especially when the crossing angle between the streams was low (30 degrees). For the (3,3) type, all participants who opted for MACR chose to perform two MACR actions, one per traffic stream.

In terms of additional track miles (see Figure 8), there are no notable differences between SACR and MACR across the traffic crossing angles. However, the variability in track miles with MACR is slightly larger as compared to SACR. This is mainly caused by how some participants used the MACR clearances in terms of choosing the locations of the merge points. Some participants choose merge points that would make aircraft fly at relatively higher crossing angles, occasionally resulting in more additional track miles. Also, with MACR, more aircraft were involved in flying additional track miles than what would be needed by implementing a series of SACR commands. In that sense, SACR enabled participants to better optimize the trajectories of individual aircraft, as could be expected.

In Figure 9, the average minimum robustness contribution after a control action was implemented can be seen. Here, ΔRBT_{min} is the difference of the average RBT_{min} before a control action and the average RBT_{min} after a control action. When the average RBT_{min} was negative, it was counted as a -1 contribution and a +1 contribution was counted for a positive change in minimum robustness. Here,

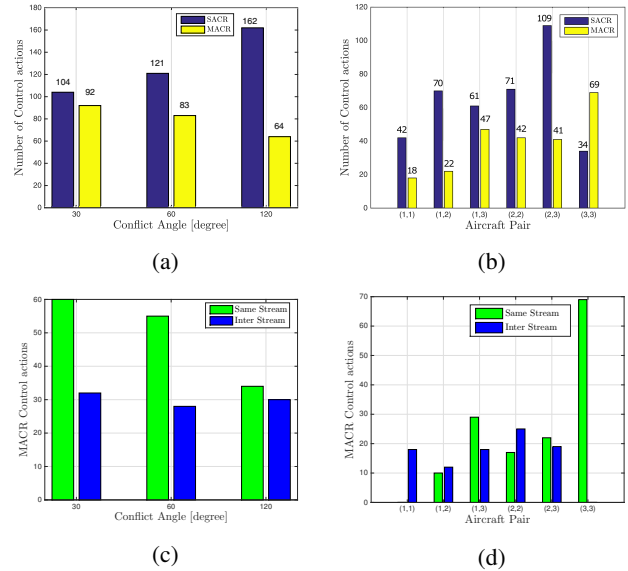


Fig. 7: Number and type of control actions categorized by conflict angles and aircraft pairs.

an increase in robustness means that aircraft are rerouted in a way such that they have increased separation margins with other aircraft and/or the no-fly-zone.

From Figure 9, it can be seen that Participant 1 executed 42 control actions (21 SACR and 21 MACR commands) and the overall impact of these control actions on the average minimum airspace robustness was +0.44. Thus compared to all other participants, Participant 1 performed the best in terms of preserving airspace robustness and was able to achieve that far better with SACR than with MACR. Whereas Participant 13 executed 38 control actions (11 SACR and 27 MACR commands), the average impact on robustness was just +0.18.

Interestingly, it can also be observed from Figure 9 that the overall contribution of using MACR commands resulted in *decreasing* the airspace robustness as compared to SACR commands. Despite that, participants preferred MACR over SACR for aircraft which were close to each other in the same stream and for traffic with low crossing/conflict angles, the choice for less-favourable merging point locations is the reason for small and mostly negative robustness contributions

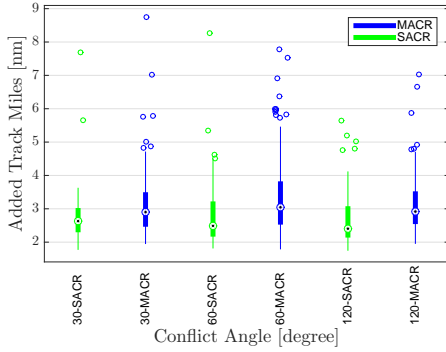


Fig. 8: Average additional track miles per aircraft.

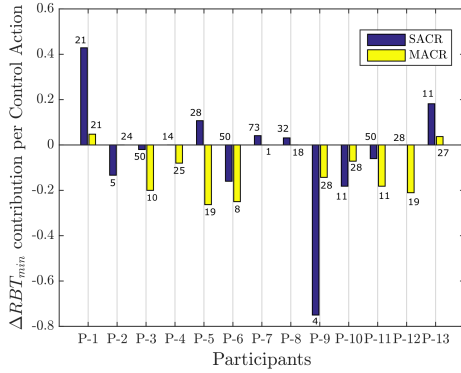


Fig. 9: ΔRBT_{min} contribution per participant, categorized per clearance type.

after a MACR control action.

V. DISCUSSION AND RECOMMENDATIONS

The motivations for enabling multi-aircraft trajectory manipulation and conflict resolution (MACR) in 4D trajectory-based operations was not only to decrease the required physical workload of controllers under increased traffic densities, but also to share the cost of reroutes between multiple aircraft. The current implementation of the MACR capability, however, did not reveal notable benefits in terms of track miles and preservation of airspace robustness. It highly depended on how and when controllers used this capability in choosing the locations of traffic merge points. As such, the current implementation of the MACR capability does not provide a significant advantage over manipulating single trajectories.

Regarding cost sharing, this study did not further consider the economics and fairness of reroutes. The definition of fairness highly depends on the perspective on “cost” for each stake holder. For example, for an airline, flying more track miles at higher speeds increases fuel burn and this might be the dominant cost factor. For an air traffic controller, experienced workload and maintaining an orderly flow of traffic might play a dominant role in their definition of “cost” (and therefore creating merge points for multiple aircraft could result in more chaos than order and structure). In the

aviation community, fairness of reroutes is still an ongoing debate, and not likely to be solved easily, given the variety of stakeholders and their views on costs.

VI. CONCLUSIONS

In this work, a variant of the travel space representation display that allows for the simultaneous control of the path of multiple aircraft was tested. In an experiment, participants used this control option mostly when confronted with aircraft on paths with small intersect angles. This created common routes for, e.g., the avoidance of a weather cell.

Compared to individual control of the flight tracks, use of the new option did not result in resolutions with larger robustness, as measured by minimum separation to other aircraft and to the weather area. The current implementation of the option can only be applied to multiple aircraft at the same time, while all these aircraft are in the sector and under control of the operator. This fact that might have contributed to a slight increase in track miles seen for aircraft when controlled jointly. Participants did attempt to organize the traffic stream into flows, however this was not tied to the option for simultaneous manipulation of multiple aircraft paths. It is to be expected that control of streams of aircraft – rather than individual control – can help in reducing the controller workload in future 4D scenarios, however, rather than only focusing on the joint control of aircraft that are simultaneously in the sector, an option of re-applying previously created resolutions to aircraft following in the stream could be explored.

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