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Flow-Based Air Traffic Control: Human-Machine Interface for Steering a Path-Planning Algorithm

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***Abstract*— In the near future, air traffic controllers are expected to adhere to stringent time and position constraints in controlling traffic. For this new task, new decision-support tools are required which include higher levels of automation, whilst letting humans remain to be the ultimate responsible for the safety of operations. In previous research, an advanced human-machine interface was designed and evaluated that allows controllers to manipulate four-dimensional flight plans of each individual aircraft. In this research, a higher level of automation is explored by designing a new interface prototype that enables controllers to manipulate multiple flows of traffic by facilitating interaction with a path-planning algorithm. A first evaluation of this interface, in which five participants were asked to structure a perturbed airspace as they saw fit, showed that the participants were able to influence the algorithm as they desired and were supported by the interface that visualized the inner workings of the algorithm. However, human influence did not improve the solutions in terms of sector robustness and efficiency, as compared the previously designed interface for aircraft. Therefore, improvements and its use case warrant further research.**

I. Introduction

Predicted increases in air traffic volumes and operational complexity due to trajectory-based operations (TBO) mean that the current way of sector-based *tactical* control by Air Traffic Controllers (ATCOs) will change to a more *strategic* form of airspace control [1]. This shift will require new tools with higher levels of automation that can support the ATCO in solving perturbations caused by unexpected disturbances (e.g., changing wind conditions, delays, etc.) [2].

ATC can be represented as a system with several nested control loops, all acting at different time scales and with changing goals [3]. In Fig. 1 the control loops are shown, where the inner loops control the faster short-term dynamics and the outer the long-term applications. Each loop represents a level of control sophistication, which relates to a level of autonomy. Thus, with increasing levels of control sophistication larger time spans are covered and automation is increased.

For the lower levels of control, a prototype decision-support tool was designed and evaluated [4]. The so-called Travel Space Representation (TSR), also known as a "solution-space interface" [3], illustrated in Fig. 2, visualizes the boundaries of safe control, by portraying a set of constraints for safe and feasible control actions for a selected *aircraft*. The shape of the available solution space is bounded by the aircraft speed envelope, the sector geometry, restricted areas (e.g., no-fly zones or weather cells) and the 4D flight plans of aircraft surrounding the selected aircraft. Each point within the safe regions of the shape represents a possible location for an intermediate waypoint that resolves a conflict (with the other aircraft and/or restricted areas) while adhering to the original planned time at the sector exit. Note that waypoints could be placed outside the shape, but such waypoints would violate the time constraints at the metering fix (i.e., causes a delay), because the aircraft cannot fly faster than its maximum speed.

Although the first evaluation results with this interface have been promising [4], the missions of aircraft still need to be controlled and manipulated *individually*, which could lead to relatively high workload under increased traffic densities. To alleviate the workload under such conditions, a higher level of automation support could be useful that can automatically re-direct *multiple aircraft* and thus manipulate *flows of traffic*. The problem with such solutions, however, is that the results of automatic path-planning algorithms can be unpredictable [5], rendering them less suitable for human supervision and adaptation. That is, the traffic pattern that results from using automated algorithms will very likely be, from a human perspective, rather chaotic, and unpredictable. But what if the human operator has control over what solutions the automation will generate? What if we could support the operator at a higher level in the sophistication hierarchy of Fig.1?

This paper presents a TSR-like interface which enables ATCOs to manage *flows* of traffic within a sector, by allowing them to *manipulate the constraints of a path-planning algorithm*. The controller can add or remove "motion" constraints for the algorithm by drawing shapes within the sector. The algorithm then takes these shapes into account in generating new flight plans that circumvent conflicts, whilst

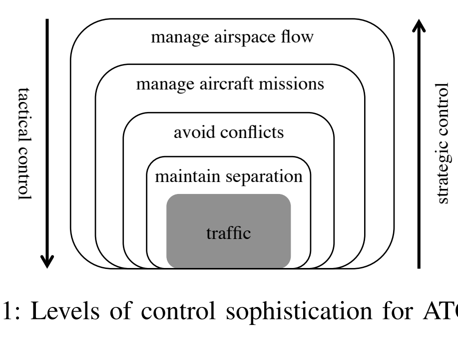

Fig. 1: Levels of control sophistication for ATC [3].

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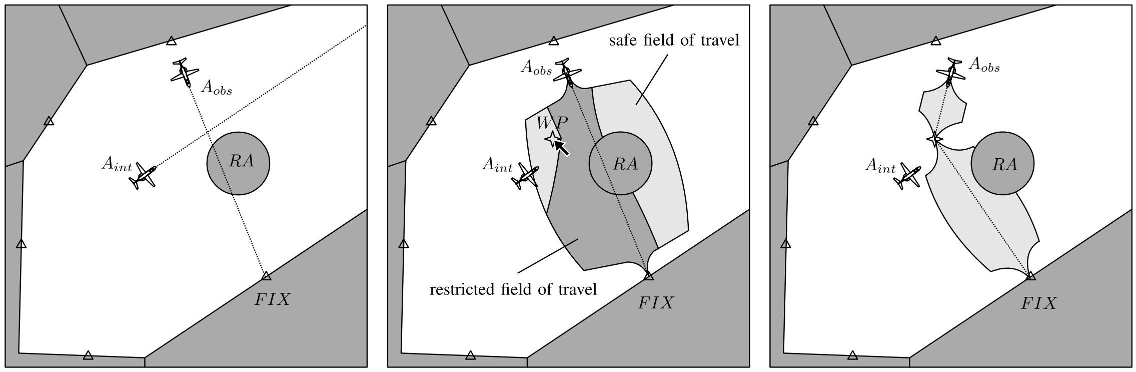


(a) (b) (c)

Fig. 2: TSR in an hypothetical traffic scenario. (a) Traffic scenario with two conflicting aircraft and a restricted airspace. (b) TSR and placement of an intermediate waypoint. (c) Resulting trajectory for the observed aircraft [4].

adhering to the metering constraints. The idea of influencing an algorithm was inspired by SUPEROPT [6], [7], which allowed controllers to define how conflicts between aircraft are solved. In addition, our study aims to make the algorithm understandable and transparent to the human controller, using a trajectory optimizer which is compatible with the solution-space interface used for managing aircraft missions [8]–[10].

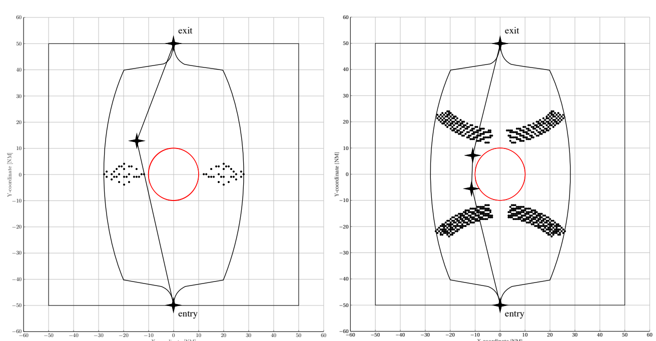
II. Trajectory Planning Algorithm

For this research, a trajectory planning algorithm is required which is suitable for human supervision and manipulation. According to the principles of human-centered automation as devised by Billings [11], the algorithm needs to be *predictable*, *observable* and *consistent* in the solutions it provides.

One promising algorithm is the Trajectory Flexibility Metric devised by Idris [8]–[10]. The approach relates to a node-based optimal algorithm and discretizes the space in position and time to account for dynamic objects. The idea behind this algorithm is that by implementing trajectory flexibility on an individual aircraft, the traffic complexity of the whole airspace can be maintained on acceptable levels and thus alleviate ATCO workload. As the algorithm is node-based, it is predictable since it follows a fixed set of rules. It is constructed such that it is not only possible to optimize for the shortest path, but also for trajectory *robustness* (i.e., "*the ability of the aircraft to keep its planned trajectory unchanged in response to the occurrence of disturbances*") and *adaptability* (i.e., "*the ability of the aircraft to change its planned trajectory in response to the occurrence of a disturbance that renders the current planned trajectory infeasible*") [9].

The philosophy underlying the flexibility metric is compatible with the solution-space concept as the solution space directly portrays the available re-routing opportunities. However, preliminary research showed that optimizing for robustness or adaptability only became useful when generated trajectories started with six to seven additional waypoints, whereas the ATCOs in the solution-space experiment usually created new trajectories with only one or maybe two additional waypoints. Here, the number of additional waypoints is therefore limited, such that the trajectories planned by the algorithm are understandable to the human controller. It was chosen to not consider robustness or adaptability in the cost function and *only* focus on the shortest path. Also, it was expected that by influencing the algorithm in combination with the shortest path as a cost, the sector robustness of the airspace could also be influenced. To increase the sector robustness, for example, the human controller could tell the algorithm to find trajectories with a larger buffer around the perturbation. Another option could be to guide two traffic streams further away from each other and as such increase the sector robustness.

Due to the discretized nature of the algorithm, the positions where new waypoints can be placed, and thus the possible trajectories that can be found are constrained. With the solution-space interface, however, the human controller is free where to place the waypoints anywhere within the shape. Fig. 3a shows the solution space, in which a trajectory



(a) One intermediate waypoint (b) Two intermediate waypoints

Fig. 3: Solution space for one and two additional waypoints. The points within the solution space shape represent the possible algorithm solutions, whereas the crosses and straight lines represent the human solutions.

has been chosen by the human controller with one additional waypoint around a perturbation. Also shown are all feasible points the algorithm can utilize to place an waypoint. Fig. 3b shows the same illustration for two additional waypoints. As can be seen, although the algorithm discretizes the solution opportunities, its solutions lie within the solution space and thus both interfaces could easily be used in conjunction.

III. Interface Design

A prototype interface has been designed for the task of rerouting 3D (i.e., 2D space and time) trajectories at a fixed altitude in a flow-based manner during the pre-tactical monitoring phase. The trajectories will be rerouted by the planning algorithm, which the human controller can influence by adding no-go areas to the algorithm. For instance, one could choose to force the automation to only find solutions at one side or to reroute around a perturbation, with possibly a certain buffer zone to increase the robustness of the airspace.

To support the ATCO in the task of constraining the automation, the work domain constraints are made visible by means of the airway solution space. This allows the human controller to reason about the placement of the constraints and the manner in which the controller would like to guide aircraft in need of a trajectory revision. The airway solution space is based on the *aircraft* solution space, which visualizes the rerouting options for one aircraft. Additionally, the algorithm also has its own constraints due to the discretized nature of the algorithm, such as the maximum number of intermediate waypoints. These constraints are visualized within the airway solution space. The airway solution space depends on a number of variables, such as: the number of waypoints, base speed, maximum speed, minimum and maximum heading and the required time of arrival (RTA) at the exit waypoint.

Fig. 4 provides an overview of the interface and the possible control actions a human controller can perform while working with the interface for a simple scenario. The numbers in the figure indicate parts of the work domain that are made visible in the interface. Fig. 4a is what will be presented to the human controller first when asked to structure the airspace to his or her own preference. The scenario shown consists of two airways (1), marked with arrows to indicate their flow direction, and a hypothetical “no-fly zone” (2) in the center of the sector.

To support the controller in redirecting a trafic flow, the airway solution space (3) (4) can be shown for a specific airway when hovering over this airway with the mouse cursor, as shown in Fig. 4b. The controller could also select multiple airways to inspect the overlapping airway solution spaces between two (or more) traffic flows (not shown). The airway solution space visualizes the limitations of the algorithm and aircraft within that flow to the controller. For this study, the number of additional waypoints was fixed to two, so if a rerouting is required, the automation will always place two intermediate waypoints, one in each curved area.

Once the ATCO decides on how to re-structure the flows, she can start placing constraints, which will guide the algorithm. In Fig. 4c it is shown how a circular shape (5) is placed around the no-fly zone. It acts as prohibited area for the algorithm for placing waypoints. It can be drawn with a slightly larger radius than the no-fly zone to implement a buffer zone, and increase the sector robustness.

In Fig. 4d an additional polygon constraint (5) is placed, which will guide the traffic West of the no-fly zone, so as to direct traffic away from the other airway. This small polygon (here, triangle) near the entry location essentially blocks off the entire right-hand side of the solution space. Without this constraint, the algorithm could choose either side of the no-fly zone to plan a trajectory, because the trajectory length around both sides would be equal.

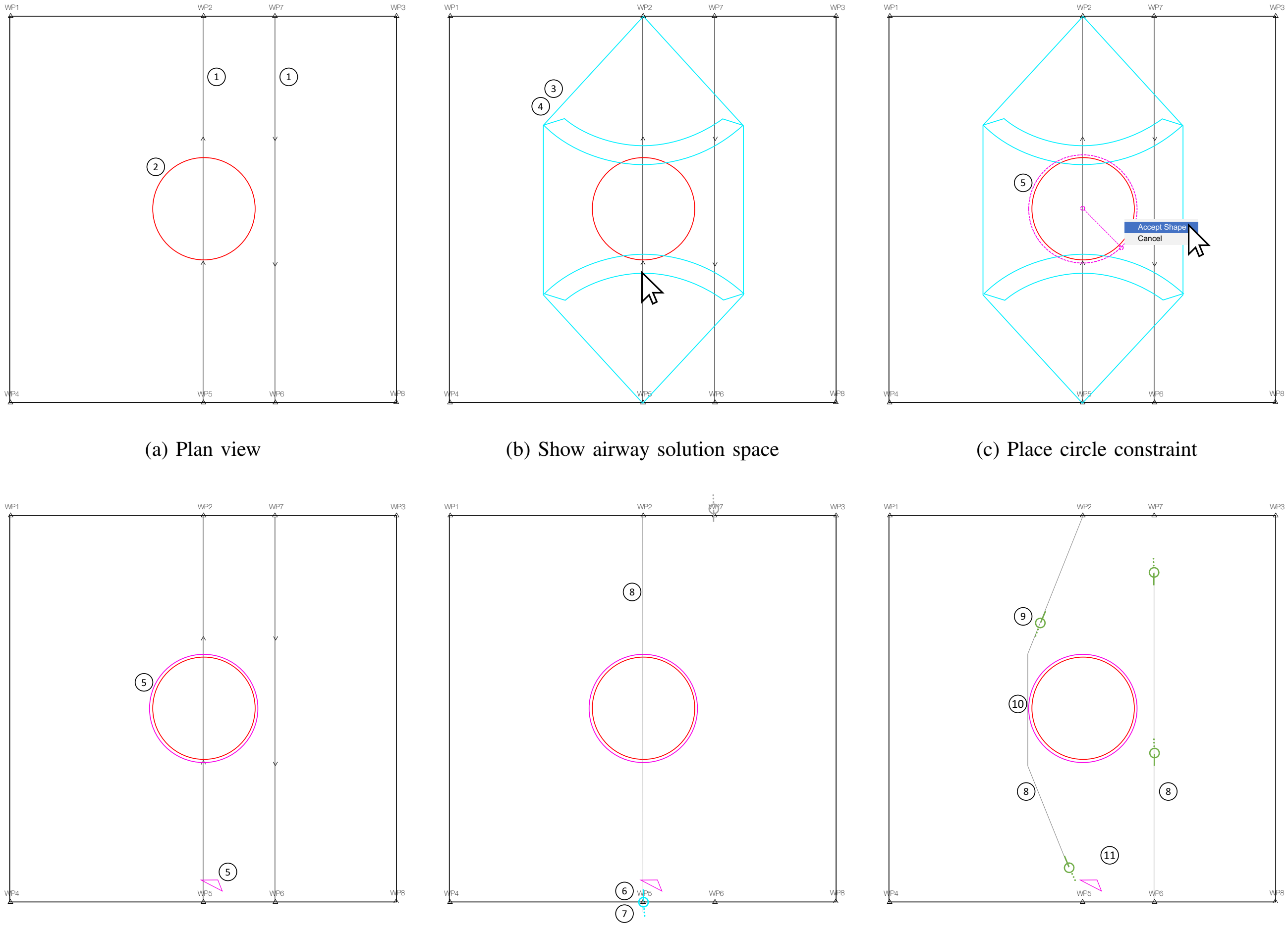
In Fig. 4e one aircraft is about to enter the airspace from the North (near WP7) and one just entered from the South (6) (near WP5). The aircraft from the South is highlighted (7), as the trajectory planning algorithm is activated to reroute *that* aircraft around the no-fly zone, taking into account the drawn constraints. The current trajectory of the aircraft is shown with the line from WP5 to WP6 (8). Finally, in Fig. 4f the result of the trajectory planning algorithm is shown, with segments (8) and (9), which bring the aircraft around the no-fly zone. All aircraft are safely separated from the perturbation (10) and without the airways affecting each other (11). Note that the algorithm also takes into account the flight plans of the aircraft in order to meet separation constraints.

IV. Evaluation of the Concept

A conceptual evaluation of the flow-based perturbation management interface has been performed, with five participants, all TU Delft aerospace engineering employees who were familiar with both ATC and solution space interfaces.

For the evaluation, participants were assigned the task of an ATCO during the pre-tactical management phase, i.e., to de-conflict traffic in a sector disrupted by a no-fly zone. Participants had no information available about the upcoming traffic, however. When hovering and selecting an airway, the airway solution space and the algorithm constraints for that specific airway were shown. With this information, participants were asked to restructure the airspace by *placing constraints*, while considering the following inter-dependent criteria: safety buffers (i.e., sector robustness), additional track length and resulting airspace structure.

To assess the performance with the flow-based interface, a conceptual airspace was designed, based on the multi-sector principle [12]. Three upper airspace sectors from the southeastern part of France where combined into one large airspace of $92,000$ km^2, see Fig. 5. In this airspace eight hypothetical airways were placed in a structured grid-based manner. In addition, a high traffic density and a low traffic density scenario were defined. The low traffic density scenario featured $\sim$ 33 flights/hour, based on the peak traffic that Eurocontrol currently sees in this airspace during summer. The high density scenario was scaled with a factor of 1.6, based on future traffic predictions [13], resulting in ~ 53 flights/hours.



(a) Plan view (b) Show airway solution space (c) Place circle constraint

(d) Placed constraints (e) Aircraft entering airspace (f) Trajectories rerouted

Fig. 4: Multiple steps in the process of structuring a simple airspace with the interface.

Both traffic scenarios were made conflict-free beforehand, based on a minimum separation distance of 5 NM. All aircraft were Airbus A320 flying at FL245, which is the lower bound of the upper airspace. This is also near the flight level which leads to the maximum performance envelope of an A320 aircraft (FL240). The two traffic scenarios were designed so that the last aircraft would enter around 45 minutes in scenario time. Thus, for the low traffic density scenario 25 aircraft would enter the airspace and 40 for the high scenario. In both traffic scenarios, perturbations were introduced by placing a large circle-shaped no-fly zone with a radius of 25 NM at three different locations (see Fig. 5). In the experiment, each participant controlled each scenario twice, rotating them 90 degrees to prevent scenario recognition.

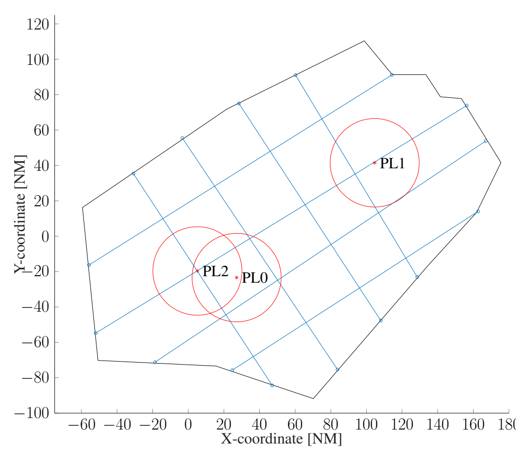
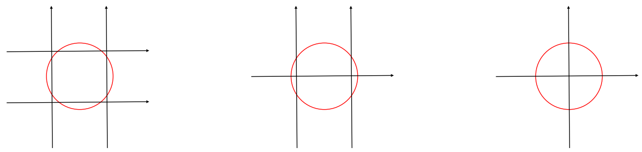


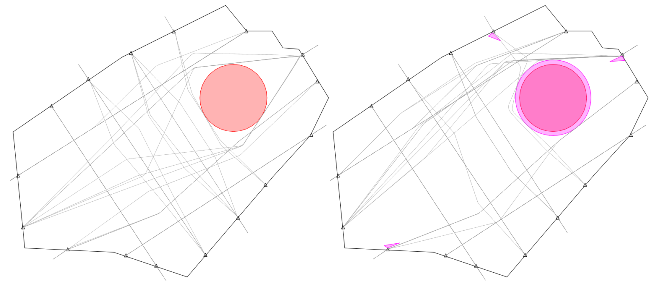
Fig. 5: Designed airspace, including perturbation locations.

To assess the outcomes of the algorithm influenced by humans, two baseline measurements were used. One was the result of full automation, where the algorithm autonomously decided how to re-route each aircraft individually without any human influence, potentially leading to (from a human perspective) "chaotic" traffic flows. The other baseline measurement had one participant controlling each aircraft individually using the TSR as designed by Klomp et al. [4]. Note that comparison with the aircraft solution space should be done with care, because the controller could reroute trajectories throughout the scenario, whereas with the airway solution space interface the controller sets his or her



(a) PL0 (b) PL1 (c) PL2

Fig. 6: Three categories of perturbation locations.



(a) Full automation (b) Participant 2

Fig. 7: Full automation solution versus the solution after the algorithm was influenced by participant 2 for the PL1 scenario.

constraints at the start of the scenario, without any knowledge of what will happen in the future and he or she does not have to ability to adjust trajectories throughout the scenario.

The perturbation location is chosen as an independent variable because preliminary research showed that the location highly influences the applied control strategies. The locations are grouped into three categories: PL0, PL1 and PL2, such that, respectively, either 0, 1 or 2 airways crossed right through the center of the perturbation, see Fig. 6. The rationale behind this is that if an airway crosses the perturbation right through the center, the human controller can make a decision to steer the trajectory algorithm left or right of the perturbation. If an airway crosses the perturbation only slightly, as with PL0 and PL1, the trajectory algorithm will *always* choose the shortest path around the perturbation. It might only pass the other side of the perturbation if the algorithm cannot find a solution the shortest way around the perturbation due to air traffic. So although for PL0 four airways are affected, and for PL2 only two, the effect that the ATCO has on the algorithm is larger.

V. Results

In Fig. 7 an example of the resulting traffic patterns in the full automation trial (i.e., the solutions generated by the algorithm were not influenced by humans) and those generated from a human-influenced algorithm are shown. From the patterns it can be observed that the human-influenced algorithm results in a less chaotic traffic structure compared to the full automation trial. In this situation, the participant choose to let aircraft clear the perturbation (i.e., the no-fly zone) with larger separation margin and enforce the algorithm to re-route all incoming traffic from the West along the North side of the perturbation and all incoming traffic from the East along the South side of the perturbation. This resulted is a more structured and predictable traffic pattern.

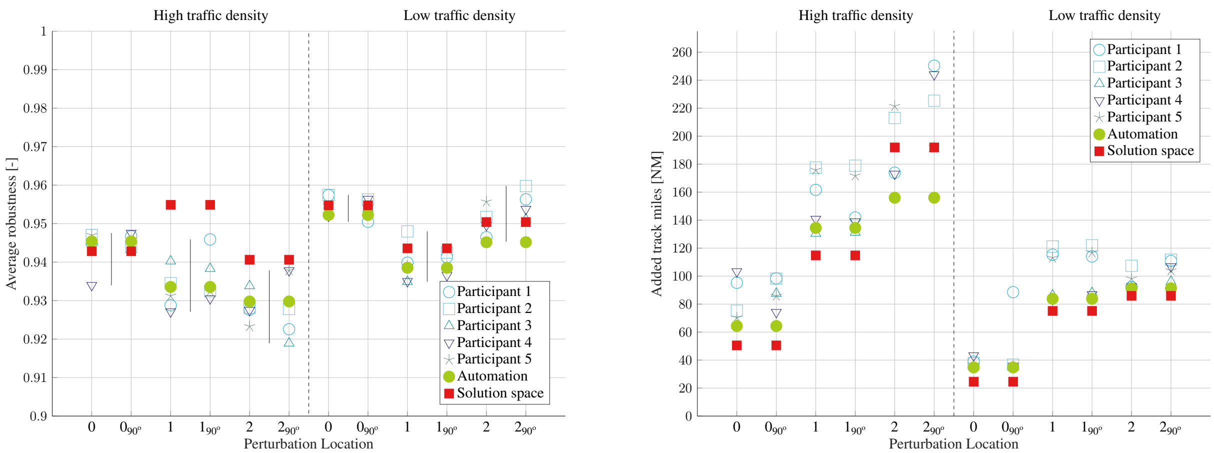
In Fig. 8a and Fig. 8b the average robustness and total addition flown track miles are shown for each participant, along with the baseline measurements (i.e., "full automation" and "working with the original TSR"). Overall, the human-influenced algorithm results in increased additional track miles, but not necessarily in increased sector robustness as compared to full automation and the TSR trials. In low traffic density, the solutions are much closer to each other than in the high traffic density. Interestingly, the TSR trials, where one participant controlled all scenarios using the TSR interface, i.e., controlling each *individual* aircraft, gave the best results in both robustness and track miles. This is most likely caused by the fact that in manually controlling each aircraft, the participant had more freedom to place intermediate waypoints and fine-tune the trajectories of aircraft after they entered the sector. For the algorithm, re-routing only occurred as soon as the aircraft entered the sector and the possible locations of such waypoints was also restricted to two areas, see Fig. 3.

From subjective feedback, participants indicated that they felt in control of how the algorithm would behave and generate its trajectories. The currently supported means for control, the polygon and circle, were rated fairly good and intuitive by most participants. However, more control over the algorithm was desired in order to generate more predictable outcomes. For example, one participant suggested to penalize certain routes (e.g., left is "mud" representing high cost, and right is asphalt, representing low cost) to avoid introducing artificially longer paths in an unwanted direction. Another suggestion was to have more information available of future traffic densities along the airways, as this would would enable better decisions by reasoning upon how the traffic scenario would emerge.

VI. Discussion and Recommendations

We aimed to design a conceptual interface for flow-based perturbation management by means of influencing a trajectory planning algorithm. The underlying motivation for this study has been to facilitate air traffic control on a higher level of sophistication, namely traffic *flows* rather than individual aircraft. Allowing humans to influence the solutions generated by the automation mitigates a possible down-side of using highly-automated control, namely the potentially "chaotic" traffic flow that emerges. This would make a sector very difficult to supervise by humans, and even more difficult for the operator to 'step in' when automation fails.

When considering individual planned trajectories, the selected node-based trajectory flexibility metric algorithm by Idris performed well in this research, and the algorithm led to predictable and consistent results. However, when considering the results of the algorithm on the whole airspace, it is



(a) Average robustness

(b) Added track miles

Fig. 8: Average sector robustness and added track miles per perturbation location and traffic density.

sensitive to human input: only a small change in constraint set-up could completely change the final set of trajectories and influence robustness and additional flown track miles considerably.

Improvements to the algorithm can be made as to where waypoints can be placed. In the current implementation it was chosen to only allow one waypoint at one third of the RTA and another at two-thirds. This led to sub-optimal trajectories, which was clearly seen when perturbations were located close to the entry or exit waypoint. To improve this, the ATCO should be given more control as to where the algorithm is allowed to place additional waypoints.

Although results from subjective feedback indicated that participants were positive about the interface (in making the constraints and limitations of the algorithm transparent and allowing them to steer the algorithm in their own preferred way), objective results show that currently the aircraft solution space interface performed better in terms of additional track miles and airspace robustness. Perhaps a better concept of operations would to use the airway solution space in combination with the aircraft solution, where the airway tool is used to roughly relay all trajectories beforehand and use the aircraft solution space to fine-tune specific trajectories to optimize for increased sector robustness and decreased additional track miles.

VII. Conclusion

We presented a conceptual interface for air traffic *flow*-based perturbation management in ATC, which enables ATCO's to reroute multiple aircraft along an airway by influencing a path-planning algorithm. A first evaluation showed that the interface supported the understanding of the algorithm and allowed for steering its solutions towards more predictable patterns. Results also indicate that the original TSR interface, by which one controls each aircraft individually, performed better in terms of robustness and added track miles. Future work focuses on combining the airway and aircraft solution space interfaces, where the former can be used to re-organize the traffic structure, at the sector level, and the latter can be used to fine-tune individual trajectories, at the level of individual aircraft.

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