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Design of an Ecological Flow-based Interface for 4D Trajectory Management in Air Traffic Control

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ABSTRACT

The concept of trajectory-based operations as proposed by SESAR and NextGen seeks to increase airspace efficiency and capacity by introducing *time* as an explicit control variable. Such form of operations lean heavily on the introduction of higher levels of automation to support the human air traffic controller in performing this new task. In previous research, and following the ecological interface design paradigm, a constraint-based decision support tool has been developed to visualize safe and unsafe fields of travel for rerouting the 4D trajectories of individual aircraft. A human-in-the-loop experiment showed that although the interface visualizes the boundaries between safe and unsafe actions, the quality of control in terms of *robustness* was mainly dependent on the level of expertise of the human controller. Following these findings, the goal of this study has been twofold: 1) to explicitly integrate the attributes of robust control actions into the constraint-based visualization, and 2) to enable flow-based (multi-aircraft) operations with the decision-support tool which is more in line with the mental model of expert controllers. As a result, a metric for the evaluation of robustness has been developed and three different types of structure-based control abstractions have been identified which have been integrated into the tool. Future work will focus on a human-in-the-loop experiment in order to evaluate the effectiveness of these two new additions.

1 INTRODUCTION

The way in which Air Traffic Control (ATC) is performed is foreseen to undergo a paradigm shift within the coming decades. Both in Europe and the US, the concept of Trajectory-based Operations (TBO) is currently being investigated as a means to handle the increasing amount of air traffic, both efficiently and safely. This concept introduces *time* as an explicit control variable for the planning and manipulation of aircraft trajectories, which will make the system more efficient and predictable [1], [2]. As a result, the task of the (human) Air Traffic Controller (ATCo) is foreseen to shift from today's fully manual tactical control by voice communication towards the strategic manipulation of 4D trajectories. This new task relies heavily on the introduction of higher levels of automation and new decision-support tools whose structures have not yet been established.

One approach to the design of decision-support tools is the Ecological Interface Design (EID) framework. This framework is based upon identifying and visualizing the constraints that follow directly from the work domain [3]. In a nutshell, such a constraint-based representation provides the controller with a map of all possible control actions, and is typically in the form of visualizing "go" and "no-go" areas. In previous work, the so called "Travel Space Representation" (TSR) was developed which visualizes the constraints for manipulating the 4D trajectory of an individual aircraft, both spatially and in time [4]. Rather than presenting optimized discrete solutions (i.e., automated advisories), the TSR visualizes the "areas of safe travel" through which an aircraft can be rerouted safely whilst adhering to its internal (i.e., performance envelope) and external (i.e., other traffic, restricted areas and timing) constraints. All control actions within these areas are "good enough", which in turn leaves the ATCo free to implement their own control strategies as a creative problem solver.

Subsequent experiments with the TSR showed that this representation indeed allows controllers to safely manage the air traffic [5]. However, these experiments also showed that controllers sometimes opted for "tight" solutions in narrow control spaces, or close to the boundaries between safe and unsafe areas. Such solutions reduce the ability of the system to cope with disturbances and therefore may threaten the long-term airspace stability. A post-hoc analysis of the robustness of individual control actions revealed that controllers with a higher level of expertise often performed more robust control strategies as compared to novice controllers [6].

Further, the previously developed TSR only supports the control of individual aircraft (one-by-one). However, the ultimate task of the controller is to achieve a safe and efficient alignment of *all traffic* within the sector. Next to the elements which directly influence the robustness of individual aircraft (i.e., additional separation buffers, conflict resolution geometry, etc.), planning ahead, sequencing, grouping and distinguishing between standard and non-standard flows have also been identified as a recurring activities by ATCo's to implement their strategies and lower their perceived workload [7]–[9].

In order to promote more robust control and to better enable expert strategies, this study aims to extend the existing TSR by supporting the following two elements: 1) to explicitly visualize the robustness of a given control action in the constraint-based representation, and 2) to allow for control through three identified structure-based abstractions.

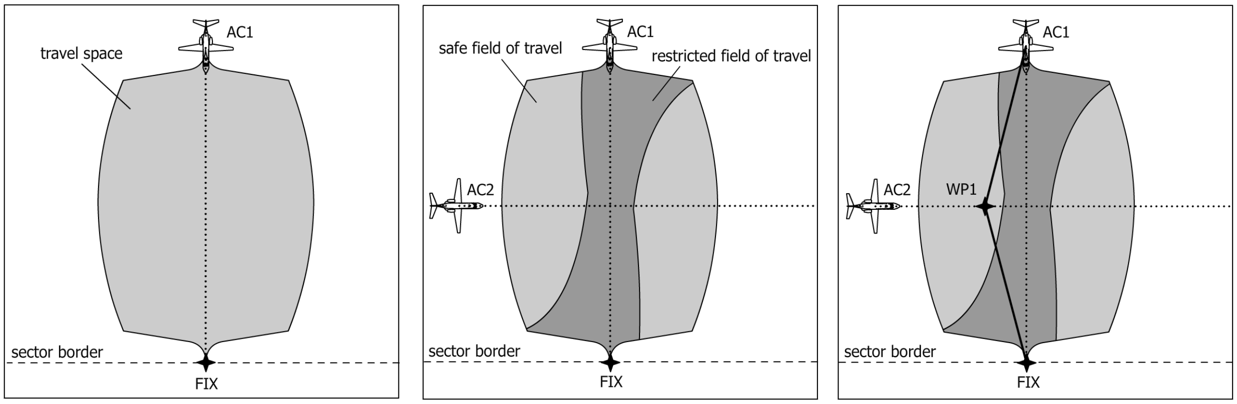
The structure of this paper is as follows. Section 2 provides a brief description of the basic principles of the TSR. In Section 3 a metric is introduced which is used to evaluate the robustness of control actions. A description is given of the identified structure-based abstractions which are used by expert controllers in Section 4. In Section 5 the new interface design is presented, followed by a discussion and conclusions.

2 TRAVEL SPACE REPRESENTATION

Following the frameworks of Cognitive Systems Engineering (CSE) and EID, the TSR has been designed as a constraint-based controller decision support tool for the "tactical monitoring phase" of 4D Air Traffic Management (ATM) [10]. Here, the automation provides meaningful representations to the human controller which allows him/her to manipulate segments of the 4D trajectory of an aircraft whilst ensuring safe and efficient operations.

To illustrate how the TSR can be used by the controller to modify the trajectory of an aircraft, consider the hypothetical traffic scenario shown in Fig. 1. Here the task involves de-conflicting two aircraft within a controlled sector whilst keeping the Required Time of Arrival (RTA) at the sector exit point FIX unchanged. In Fig. 1(a), the selected aircraft (AC1) is shown, and the flight segment towards point FIX is indicated by a dotted line. The *travel space* of AC1 is shown in light grey; its boundaries delimit the zone where the introduction of an intermediate waypoint into the flight segment will result in a new trajectory that is feasible with respect to the aircraft performance limits (i.e., turn radius and maximum speed) and the RTA at the point FIX.

A conflicting aircraft (AC2) is introduced in Fig. 1(b). As a result, part of the travel space of the selected aircraft becomes restricted. This *restricted field of travel,* shown in dark grey, indicates the area in which the placement of an intermediate waypoint will result in a loss of separation with the other traffic at a given time in the future, rendering this control action as unsafe.



(a) TSR of AC1 (b) TSR of AC1 affected by AC2 (c) Conflict resolution for AC1

Figure 1: *Overview of the Travel Space Representation*

Fig. 1(c) shows how the controller can identify and select any location in the *safe field of travel* to place an intermediate waypoint. The illustrated control action results in the original flight segment to be replaced by two new flight segments with equal speed such that the conflict is avoided and the RTA at the exit point remains unchanged.

However, although proven useful for visualizing the safe zones for the modification of a single trajectory, the TSR neither provides information about how robust a control action is nor allows to manipulate more than one aircraft for a cooperative resolution. Despite that the areas of safe travel for the selected aircraft are visualized, the impact of one control action on the robustness of the other aircraft and of the system are not immediately apparent. The next section describes a new metric to calculate the robustness of such a control action with the TSR.

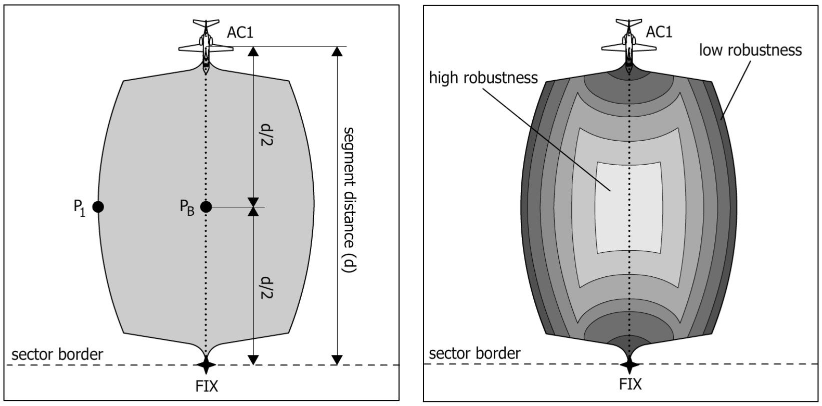
3 TRAJECORY-BASED ROBUSTNESS

In previous research, robustness (RBT) was identified as a "hidden" motivation that expert controllers use to perform adequate control decisions [6]. Introduced by Idris et al., RBT has been defined as "the ability of a flight to adhere to planned trajectory and imposed constraints, despite probabilistic random state deviations from that trajectory", such as traffic or weather activity [11], [12]. In those studies, RBT was used as one of multiple measures to determine the "best" trajectory from a set of recursively generated trajectories, and was mainly intended for automated Conflict Detection and Resolution (CD&R) algorithms.

Based upon the same underlying principles of reachability and available control space, the metric has been adapted in this study to allow for the evaluation of the robustness of a control action at any given location within the travel space of a selected aircraft. The ultimate goal is to promote robust control by directly visualizing the robustness of a given control action on the TSR. For this purpose, two elements of robustness have been identified; *control space robustness* and *conflict robustness.*

3.1 Control Space Robustness

The control space robustness is a measure to evaluate the flexibility in arrival times at an intermediate waypoint visualized in the travel space. This measure is related to the range of times at which a an aircraft can pass through this intermediate waypoint and can still achieve the planned RTA at the destination fix. A large time range indicates that there is additional flexibility to change the arrival time at this intermediate point, and is therefore more robust to perturbations (i.e., conflicts, deviations from the flight path, etc.). Conversely, a small range of feasible times indicates that the timing options at the waypoint are limited which could reduce the robustness of this trajectory.



(a) TSR of AC1 with two possible control actions

(b) Control space robustness in the travel space of AC1

Figure 2: *Schematic overview of control space robustness in the Travel Space Representation*

To illustrate how control space robustness can be calculated and interpreted, consider the selected aircraft, AC1, in Fig. 2(a). Neglecting wind, in the extreme case when the aircraft is rerouted through a point on the border of the travel space (point P_1), the additional track length requires the aircraft to continuously fly at its maximum speed along the entire trajectory in order to achieve the planned RTA at point FIX. In case of a perturbation, any speed/time change at the intermediate waypoint will result in the destination RTA to be broken. In fact, at all rerouting points exactly on this border the aircraft will have no margin in terms of allowable arrival times.

Now consider an intermediate waypoint at the point exactly in the middle of the current trajectory segment (point P_B). At this point, the resulting trajectory has the largest possible range of arrival times at the waypoint as compared to all other positions within the TSR. That is, in case of a conflict with other traffic or a deviation from the flight path, the control space of the trajectory in terms of arrival time at the waypoint is largest in order to resolve the conflict and meet the RTA.

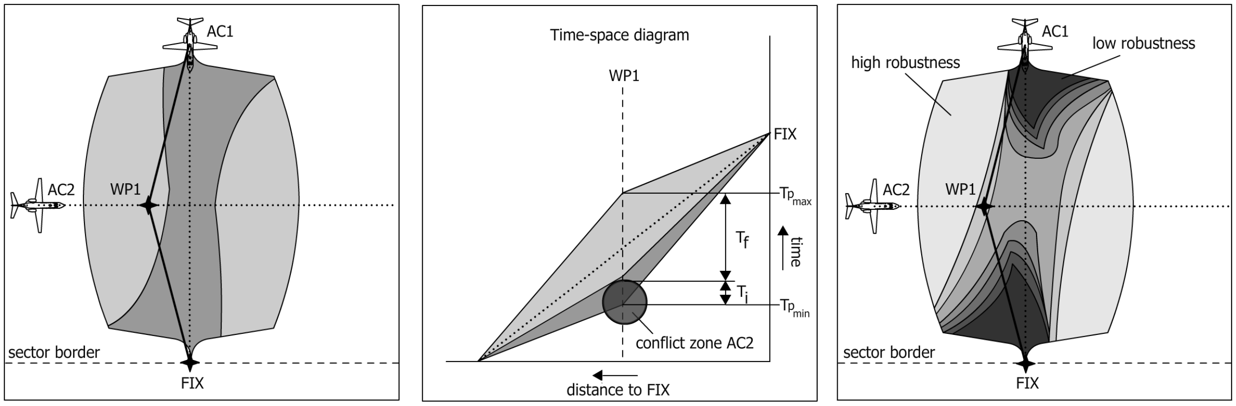
Because the shape and size of the TSR depend on the distance towards the next waypoint, the fixed RTA and the aircraft performance envelope (i.e., the maximum and minimum speed), the measure which quantifies control space robustness for a given location in the TSR is chosen to be relative to the largest possible range of arrival times (at point P_B):

$$RBT_{CS} = \frac{T_{P\max} - T_{P\min}}{T_{B\max} - T_{B\min}} \tag{1}$$

Fig. 2(b) shows a schematic representation of the TSR which includes gradient lines indicating how the control space robustness varies with respect to the placement of an intermediate waypoint. The image has been traced from a computer-based simulation.

3.2 Conflict Robustness

Conflict robustness is the fraction of the available control space at the given intermediate waypoint (i.e., between $T_{P\max}$ and $T_{P\min}$) which will result in a conflict free trajectory. For example, when rerouting an aircraft in an empty sector, all possible arrival times at the intermediate waypoint will not lead to a conflict with other traffic. Here, although the control space robustness might be low, the robustness against conflicts is high. In the presence of other traffic, however, certain available arrival times may lead to a conflicting trajectory.



(a) Hypothetical traffic scenario (b) Control space of AC1 affected by AC2 visualized in the TSD (c) Conflict robustness in the travel space of AC1

Figure 3: *Schematic overview of conflict robustness in the Travel Space Representation*

To better illustrate this, a hypothetical traffic scenario has been sketched in Fig 3.(a). The travel space of the selected aircraft (AC1) is shown, and a second aircraft (AC2) is present in the sector. In this example the conflict robustness is investigated of the control action of rerouting AC1 through a given intermediate point (WP1). Fig. 3.(b) shows the Time-space Diagram (TSD) [13] of this observed trajectory. Here, the distance to go along the trajectory to the exit point FIX is shown on the x-axis. The y-axis indicates future time. The time-space line of AC1 is shown, and the available control space at point WP1 is bounded by the aircraft performance envelope. Due to the presence of the AC2, a conflict zone is introduced in the TSD. The conflict zone indicates at which times the trajectory of AC1 is occupied by AC2. The TSD also shows the arrival times at WP1 which would lead to a loss of separation (infeasible times, T_i) and the arrival times which would result in a conflict free trajectory (feasible times T_f). The measure of conflict robustness is then given by the fraction of feasible times compared to the complete control space:

$$RBT_C = \frac{T_f}{T_f + T_i} \tag{2}$$

Fig. 3(c) shows a schematic representation of the TSR which includes gradient lines indicating how the conflict robustness varies with respect to the placement of an intermediate waypoint. As for the control space robustness, this image has been traced from a computer-based simulation.

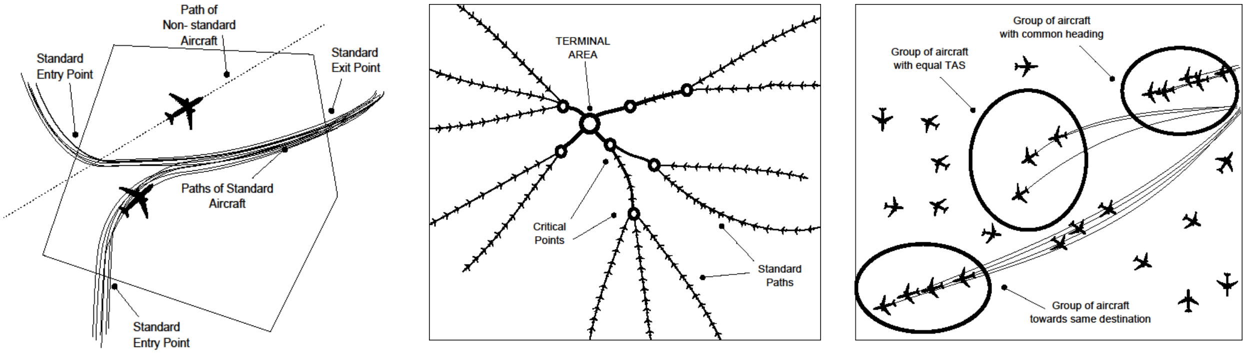
3.3 Combined Metric

It is important to point out that both Control Space and Conflict robustness metrics need to be combined in order to calculate the total RBT associated to an intermediate waypoint. The combined value of robustness for each point (P) that will ultimately be visualized in the constraint-based interface is given by:

$$RBT = RBT_{CS} * RBT_C \tag{3}$$

4 STRUCTURE-BASED ABSTRACTIONS

The concept of structure-based abstractions in ATC was introduced by Histon et al. when studying the complexity factors that influence ATCo decisions [9]. Structure-based abstractions can be seen as patterns that can reduce the perceived complexity of the system by making its evolution in time more predictable.



(a) Standard flows (b) Critical points (c) Grouping

Figure 4: *Structure-based abstractions (adapted from Histon, 2002)*

Trajectory-based ATC can be portrayed as a system that bases its actions from the intentions and value structures of the world, therefore being adaptable and capable to address a given scenario in more than one single way [14]. In this regard, Rasmussen pointed out that actions required in a decision making process would largely depend on the capacity of the human operator "to adapt to the requirements of the system under the specific situation", and to modify the strategies they have to reduce the perceived complexity. That is, to re-structure the problem in order to develop a simpler "representation of the internal state of the system" by any of the following techniques: aggregation, abstraction or analogies to ready-made solutions [15].

The development of the proposed flow-based manipulation of traffic in the TSR comes from an abstraction of the system's properties to a higher level of representation. Moreover, attention is given to the group of "physical and informational" instances that define the structure of the ATM system, which from previous observations "was identified as an important factor in both sources of cognitive complexity and the strategies used to reduce cognitive complexity" [9], [16]. The three types of abstractions were identified by Histon et al. and are herein explained.

4.1 Standard Flows

Standard Flows are considered to be the most used structure-based abstraction by the ATCo. Some are formed by explicit structural elements in the sector, while others result from "common practices or standardized but unpublished patters of operation". The definition arises to differentiate "standard" from "non-standard" traffic movements, whether they belong to a defined flow pattern in a sector or not. For instance, Fig. 4(a) sketches the situation in a generic sector where aircraft flying along a similar path can be classified as a common category of aircraft which can be considered as standard. Conversely, an aircraft following a unique route through the sector can be classified as a non-standard aircraft in the scenario.

Histon et al. continue that "the task of projecting the future behavior of aircraft that belong to a standard flow is greatly simplified by the generalized expectation of its trajectory"; i.e., the benefits of such arrangement resides on the powerful simplification of the projection task, which could be harder for the "special case" or non-standard aircraft that do not comply with the operating rules of the identified pattern. Moreover, the simplification quality of the standard flow makes the number of flying aircraft a less important factor to the complexity of the ATC system.

4.2 Critical Points

The ATCo often focusses on a limited set of critical locations, which ultimately "eliminates the need for controllers to evaluate the potential for conflict over all possible pair of aircraft within the flows". For instance, the actions of resolving conflicts at a common location such as a crossing point of two standard flows is reduced to a temporal problem. Hence, the cognitive effort required to separate traffic is reduced with the presence of critical points.

To illustrate this, the white circles in Fig. 4(b) represent the merging points of different trailing streams of traffic (standard flows) arriving into a generic Terminal Area (TMA). Rather than focusing on deconflicting each individual aircraft pair, the controller now only has to focus their attention on the set of critical points.

4.3 Grouping Abstractions

In the absence of standard flows, groups of aircraft which share common properties can be identified to reduce the perceived complexity of a traffic situation. For instance, if two or more aircraft that are in the vicinity of each other follow a common heading and speed, they can be grouped in terms of intent. Consequently, groups of aircraft can be addressed as one entity to manage situations that are common to each of the aircraft. One example of this could be rerouting a group of aircraft around a weather cell. Fig. 4(c) shows an example of three different types of grouping; by speed, by heading, and by destination. Structured-based abstractions are representations that may simplify the task of the ATCo by allowing him/herself to structure a traffic scenario in order to better project future traffic situations.

5 INTERFACE PROTOTYPE

The ATC system is undoubtedly a highly complex environment with many interrelations which are not directly salient to the user. The aforementioned robustness metric and structure-based abstractions aim to capture and integrate a part of these relationships in order to provide the controller with a more meaningful representation than the available travel space alone. In this section an interface design is proposed in which the explained structures and metrics are implemented.

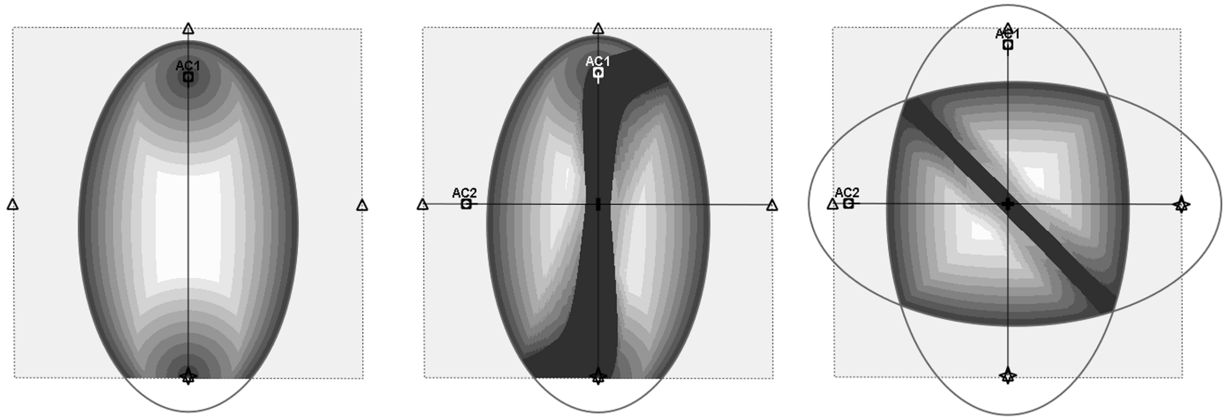
5.1 Robustness

As described in Section 3, the robustness metric can directly be visualized in the travel space representation of a selected aircraft. The screenshots in Fig. 5 have been taken from the computer-based prototype interface. In this simulation, a generic commercial aircraft type has been used, flying through a square 200NM by 200NM sector, at FL300, and at the average speed between minimum and maximum speed (M.68).

Fig. 5(a) shows how the control space robustness is visualized in the travel space by selecting AC1. In this prototype, the travel space was bounded by an ellipse. As in the previous TSR the ellipse is a function of the flight envelope of the aircraft and the timing constraint at the exit point. Any waypoint placed outside of the ellipse will result in flight AC1 be unable to accomplish the RTA.

In Fig. 5(b) a second aircraft (AC2) has been added which is in conflict with AC1. The dark gray area represents the restricted field of travel where the placement of a waypoint will not resolve the conflict by flying along two equal-speed segments (similar to the restricted field of travel). In addition to control space robustness, the gradient now also shows the areas which are less robust due to the occupied fraction of control space by the other aircraft (close to the restricted field of travel). At such points, the possibility for aircraft to absorb perturbations in the future is reduced and could motivate the operator to maintain a larger separation buffer to maintain a high robustness.

In Section 3, only the manipulation of a single aircraft was considered. However, the underlying principles of the representation can also be applied to the control of multiple aircraft simultaneously. Fig. 5(c) shows the robustness of a combined (coordinated) conflict resolution by selecting AC1 and AC2. Here, the travel space is bound by the overlapping area of both performance ellipses. The visualized robustness relates to the minimum robustness of AC1 or AC2 as a result of the combined resolution.



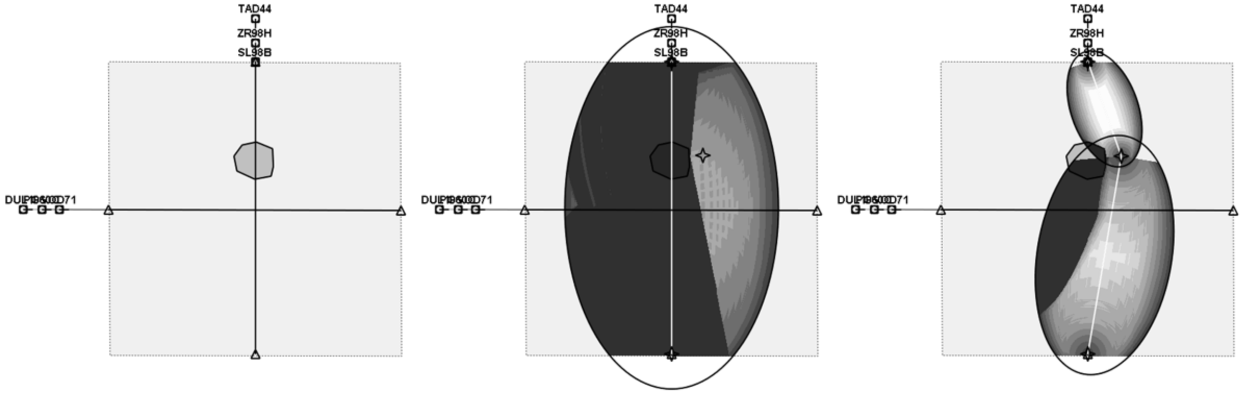
(a) AC1 control space robustness (b) Robustness of AC1 affected by AC2 (c) Robustness of a combined resolution for AC1 and AC2

Figure 5: *Prototype visualization of robustness*

5.2 Structure-based Abstractions

The structure-based abstractions focus on simplifying the perceived complexity of a given traffic scenario by focusing on groups of aircraft with common properties rather than all aircraft individually. The prototype interface promotes this type of control by allowing the manipulation of multiple aircraft simultaneously. The following paragraphs describe how the three identified structure-based abstractions are reflected in the interface prototype.

Standard Flow Control:
In order to control standard flows, the concept of *master routes* has been adopted. A master route is defined as a common route that multiple aircraft intend to follow. Fig. 6(a) shows a scenario with two steams of aircraft; a southbound and an eastbound stream. In this scenario, the presence of a restricted area requires the southbound stream to be rerouted. Fig. 6(b) shows how, by selecting the southbound master route, the combined travel space is visualized for all aircraft inbound to that route. Fig. 6(c) shows how the master route can be manipulated to find a common solution for all southbound aircraft which is both safe and robust.



(a) Scenario with multiple streams of aircraft (b) Travel space of the master route of the southbound AC (c) Standard flow manipulation for all southbound AC

Figure 6: *Standard flow control*

Grouping Control:
As shown in Fig. 5(c), grouping control is enabled by the option to select multiple aircraft for which the combined travel space is then visualized. This travel space is bound by the combined performance ellipses of all selected aircraft, and the minimum resulting robustness of any control action is visualized. Fig. 5(c) shows how two aircraft on different routes can be selected to find a cooperative conflict resolution. However, groups of aircraft with common properties such as a similar master route, heading, or speed can also be manipulated simultaneously.

Critical Point Control:
Critical points are defined as the points where the routes of standard flows or grouped aircraft cross each other. Controlling traffic by means of standard flows and grouping control will allow the controller to manipulate the location and number of critical points present in the sector.

6 DISCUSSION

Previous experiments have shown that controllers with a higher level of expertise perform more robust control actions with the constraint-based Travel Space Representation as compared to novices. In this research the TSR has been modified to directly visualize the effect to robustness of a given control action to promote robust control by all controllers. Further, air traffic controller heuristics have been supported in the form of flow-based traffic control. As a result of these additions, the following behavior from the novice and expert user group are expected when using this display.

6.1 Novices

Due to their limited amount of experience, novices controller have shown to perform a more short-term, “if-then” type of reactionary control without extrapolating the implications to a system-wide level. By directly visualizing the robustness of control, it is expected that novice controllers will generally perform more expert-like control actions. If visualization the robustness metric is disabled, it will be unlikely for them to grasp how the robustness of the system is affected due to its complexity and their limited experience. However, perhaps the learning curve for adequate control actions could be reduced by using the interface.

6.2 Experts

Expert controllers are assumed to have a deeper understanding of the work domain and its complex interrelations. As experts reason about control actions according to their own mental model of the system, they are more likely to use the visual presentation of robustness as a validity check for their decisions rather than as a motivation. Further, expert controllers are expected to benefit most by the introduction of the new flow-based control options for manipulating the traffic. Instead of controlling individual aircraft, the expert controllers will now be able to directly manipulate the higher level structure-based abstractions within the traffic. This is foreseen lower the perceived complexity, and therefore to reduce workload.

7 CONCLUSION

The objective of this research has been to design an interface which promotes robust control of aircraft and supports the current structure-based heuristics of air traffic controllers. The final prototype resembles the travel space representation form, and allows the controller to organize and manipulate the 4D trajectories of multiple aircraft simultaneously. The proposed robustness metric combines the available control space of the aircraft with external separation constraints which follow from other traffic, thus showing the capacity of a given control action to absorb uncertainties. Further, air traffic controller heuristics such as standard flows, critical points and grouping abstractions are directly supported by the interface. It is expected that these additions will lead to more robust, better quality decision-making with the TSR, especially for novice controllers. Future work will include a human-in-the-loop experiment to quantify the effect to control-based robustness of the herein mentioned decision-support tool.

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