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Ecological Interface Design: Sensor Failure Diagnosis in Air Traffic Control

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Abstract: Future air traffic control will have to rely on more advanced automation in order to support controllers in their job of safely controlling increased traffic volumes. A prerequisite for the success of such automation is that the underlying data driving it is reliable. Current technology, however, still warrants human supervision in coping with (data) uncertainties and consequently in judging the validity of machine decisions. In this paper the Ecological Interface Design (EID) framework is explored to assist controllers in fault diagnosis using a prototype ecological interface (called the Solution Space Diagram) for tactical conflict detection and resolution in the horizontal plane. Results from a human-in-the-loop experiment with sixteen participants indicate that the ecological interface with explicit presentation of the means-ends relations between higher-level functional goals and lower-level physical objects (i.e., aircraft) enables improved sensor failure detection. Especially in high complexity scenarios, this feature had a positive impact on failure detection performance.

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1. INTRODUCTION

Predicted air traffic growth, coupled with economic and environmental realities, force the future Air Traffic Management (ATM) system to become more optimized and strategic in nature. One important aspect of this modernization is the utilization of digital datalinks between airborne and ground systems (e.g., Automatic Dependent Surveillance - Broadcast (ADS-B)) to facilitate the introduction of more advanced and more sophisticated automation. A prerequisite for the success of such automation, is that the underlying data driving it is reliable. However, alarming results with respect to ADS-B latencies and horizontal position accuracy indicate that broadcasted position errors could reach up to 7.5 nautical miles (Ali et al. (2013); Cedrini et al. (2010); Rekkas and Rees (2008); Zhang et al. (2011); ICAO (2013)), making tasks such as fully autonomous conflict detection and resolution (CD&R) error prone. Consequently, the human controller remains responsible for judging the validity of machine-generated decisions.

In an effort to support the human controller in such a task, the Ecological Interface Design (EID) framework is explored to make automation more transparent and hence improve the detection of sensor faults and judge the validity of automation advisories (Borst et al. (2015)). To this end, a prototype ecological interface called the Solution Space Diagram (SSD) for CD&R in ATM will be used (Borst et al. (2012)). The SSD reveals how traffic surrounding a controlled aircraft limits its solution options in heading and speed by means of velocity obstacles. Although the SSD has been studied in the context of decision-making, it has not yet been investigated in terms of sensor failure detection and the role of explicitly representing the so-called "means-ends" relationships between the aircraft plotted on the Plan View Display (PVD) and the velocity obstacles plotted in the SSD. We hypothesize that presenting these links will expedite fault diagnosis and monitor automation decisions to pending separation conflicts. Note that the topic of EID and sensor failure, and the explicit representation of relationships between display features, has been studied before in process control (e.g., St-Cyr et al. (2013); Burns (2000)), but not yet in the context of aviation featuring fast dynamics and short time constants.

This paper is structured as follows. First, the SSD will be briefly explained, followed by the experimental design of the human-in-the-loop study. After the results, a discussion and conclusion will be provided.

2. THE SOLUTION SPACE DIAGRAM AND THE PROPAGATION OF SENSOR FAILURES

The SSD is a constraint-based interface, designed according to the EID principles, using the state of an aircraft (internal performance constraints) and external separation criteria in terms of a Protected Zone (PZ) to indicate the solution space in terms of heading and speed. This enables controllers to detect conflicts (when the speed vector of a controlled aircraft lies inside a conflict zone) and avoid a Loss of Separation (LoS) by giving heading and/or speed clearances to aircraft in order to direct the speed vector outside a conflict zone (Fig. 1).

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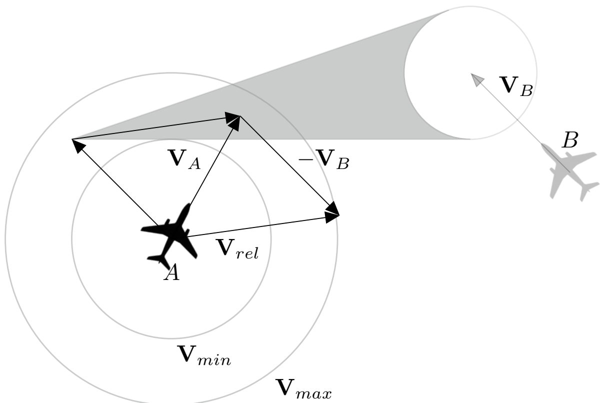
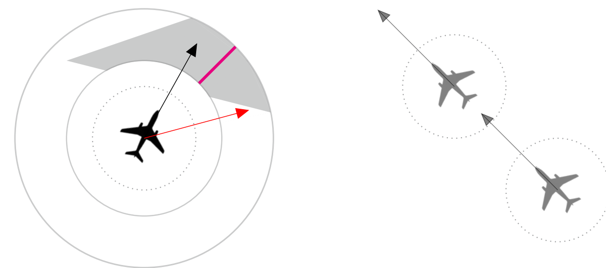


Fig. 1. The SSD, showing the triangular conflict zone (imposed by aircraft B) within the speed envelope of aircraft A.

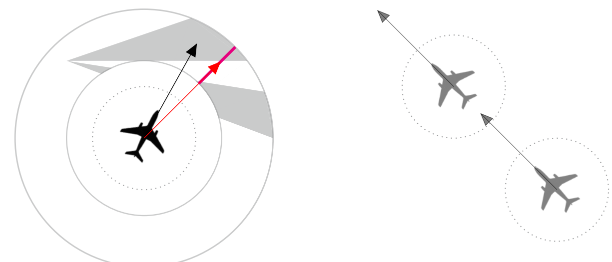
The shape and orientation of the conflict zone can give the controller information about the location and proximity of neighbouring aircraft. That is, the cone of the triangle points toward, at a slight offset, the neighbouring aircraft and the width of the triangle is large for near-by aircraft and small for far-away aircraft. Additionally, drawing an imaginary line from the aircraft blip toward the tip of the triangle indicates the absolute speed vector of a neighbouring aircraft. As such, with the shape and orientation of the conflict zones, a controller would be able to link aircraft to their corresponding conflict zones.

To construct the SSD, however, detailed information about the position and velocity vectors of aircraft need to be available, for example through ADS-B. It is also very likely that in the transition phase toward using ADS-B as a primary means of surveillance, position information will remain available from primary and/or secondary surveillance radar given the inaccuracies in current ADS-B systems. This implies that discrepancies between ADS-B and the radar image may arise, resulting in an ambiguity between the aircraft position shown on the PVD (source: surveillance radar) and the representation of the conflict zone (source: ADS-B).

Additionally, CD&R automation may generate advisories (and plot them within the SSD) based upon faulty ADS-B information, potentially masking the ambiguity and thus make it difficult for the controller to judge the validity of the given advice. In Fig. 2 an example traffic situation is shown that illustrates the ambiguity between correct aircraft positions plotted on the PVD and the conflict zones plotted in the SSD in case of ADS-B position errors. Although the advisory may appear to be correct as shown in Fig. 2(b), the conflict zone formed by the aircraft in the lower right corner does not match its image shown on the radar plot. That is, the SSD suggests the trailing aircraft is much further behind the leading aircraft. This results in an erroneous solution space between the two conflict zones, suggesting that the controlled aircraft can safely be vectored in-between the two neighbouring aircraft. Although in this situation the fault could be easily spotted, one can imagine that in more dense and complex traffic situations this error is much harder to detect.



(a) Conflict geometry and advisory without failure.



(b) Conflict geometry and advisory with failure.

Fig. 2. The effect of sensor failures on the SSD and resolution advisory.

Several studies investigating EID and sensor failure detection have shown that making the relationships between functional constraints and interface objects more explicit will improve fault diagnosis (see Burns (2000); St-Cyr et al. (2013)). In this context, making the relationships between the conflict zones in the SSD and the aircraft on the PVD more explicit should expedite fault diagnosis. But is this also true when the work domain dynamics are fast and complex, requiring swift and correct controller responses?

3. EXPERIMENT DESIGN

An experiment has been designed and conducted, to investigate whether or not explicitly representing the means-ends relations between aircraft and their conflict zones positively contributes to sensor failure detection and diagnosis, irrespective of traffic complexity.

3.1 Participants and tasks

Sixteen participants volunteered in the experiment, all students or researchers in the Control & Simulation (C&S) department of Aerospace Engineering at TU Delft. Their experience varied from working in Air Traffic Control (ATC) and ATM domains to aircraft control systems.

The control task given to the participants was two-fold, namely:

(1) **Conflict resolution task:** The primary control task was to ensure safe separation (at least 5 nautical miles) between aircraft by resolving conflicts highlighted by automation.
(2) **Exit clearance task:** The secondary control task was to ensure all aircraft exit the sector airspace at their designated exit points.

To simulate a supervisory control setting featuring a high level of automation, both control tasks could be com-

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