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Visualization of Pairwise Conflict Resolution for Air Traffic Control

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Air traffic capacity is mainly bound by Air Traffic Controller (ATCo) workload, which leads to problems in the view of the steadily increasing demand for air transport. Additional automation tools to support the ATCo in his current working practices are necessary. Visualization of control possibilities for aircraft by means of the "Solution Space" approach provides a first step in this direction. However, these visualizations focus on the control possibilities for a single aircraft, and a known problem is relating the indicated conflict back to the involved aircraft. This paper discusses the design of a visualization that shows the maneuvering options for a pair of aircraft in a conflict. As for the previous solution-space based display, the Ecological Interface Design framework is used to develop the design. The interface allows the ATCo to decide which aircraft should maneuver to most efficiently solve a conflict, or assists in selecting a joint maneuver, in which both aircraft make smaller maneuvers to solve the conflict. The manner in which the interface answers the requirements discovered with the work domain analysis and task analysis is discussed.

Currently, Air Traffic Controllers (ATCo's) perform a sector-based tactical form of control. They are responsible for planning and managing traffic within their assigned airspace, often with little help from automated tools. With the slow, but accumulating increase in air traffic, this makes the task of an ATCo a very demanding one, requiring an extensive selection process to find individuals capable of performing this task and a long training.

Limited automation is available, normally in the form of conflict detection probes or path prediction visualization. More recently, interfaces based on the visualization of "Velocity Obstacles" are being developed. Velocity Obstacles (VO) is a term originating from robotics – although similar theories considerably predate robotics (e.g. the Battenberg Course Indicator), and present the set of velocities of a robot (or, in our case a vehicle) that will result in a collision with another moving object. In aeronautics this has been labeled the "Solution Space", and interfaces employing this concept present the blocked velocities and heading for a selected aircraft (Mercado-Velasco, Mulder, & van Paassen, 2010; Abdul Rahman, van Paassen, & Mulder, 2011; Lodder, Comans, van Paassen, & Mulder, 2011).

Using such a representation, one can determine the safe heading and speed for the aircraft under control. However, in the case of conflicts involving two aircraft, which is by far the most common case, such a tool would be of immediate use only when the conflict is solved by maneuvering only one of the two aircraft. Judiciously applied one can also use the tool to solve only part of the problem with one aircraft, and then proceed by using the tool on the matching aircraft in the problem to complete the solution. This paper explores the possibilities to develop a visualization that that can support an ATCo in solving a two-aircraft conflict by having the two aircraft in the conflict both contribute with a maneuver.

Scope of the work

Air traffic control tasks differ considerably for different sectors. Large upper airspace sectors mainly deal with monitoring of overflying traffic. Most conflicts from crossing traffic are solved by assigning different altitudes to the traffic.

Approach sectors have less crossing traffic, and the main focus of the work is on departing and arriving traffic. Arriving traffic normally needs to be delivered to an arrival sector through one or more exit waypoints and most traffic needs to be brought to a single flight level (altitude) for the exit waypoint. Likewise, traffic that departs from an aircraft enters such a sector from one or a few entry points, and needs to be cleared for a climb to cruise altitude.

In the current practice, aircraft that are in a descent or climb need to be separated horizontally from all traffic at and between their current flight level and the flight level the aircraft has been cleared to climb or descend to. That is, the ATCo cannot make any assumptions about the climb or descent speed of an aircraft, and cannot assume that aircraft can cross

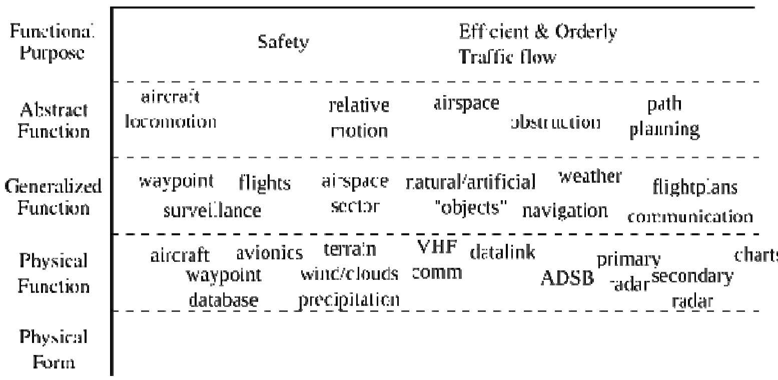

Figure 1: Work Domain Analysis for the task of Air Traffic Control.

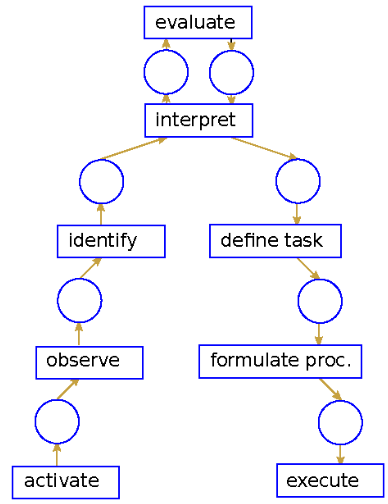

Figure 2: Rasmussen's decision ladder (Vicente, 1999)

with vertical separation, unless the ranges from current to assigned flight levels for both aircraft are disjunct with the required minimal separation between them. This makes horizontal separation a valid task for these situations, and one that cannot be always substituted by vertical separation solutions.

This paper focuses on the control task in horizontal separation. We consider control in the vertical dimension separate from this task, i.e., this control task may be applied to aircraft with overlapping vertical ranges in a descent or climb, or aircraft that is already brought to the desired altitude and it is not desirable or feasible to solve a conflict with vertical separation.

The main focus of the paper will be on the design of a support interface for horizontal separation of pairs of aircraft (which thus can include climbing and descending traffic with overlapping current and cleared flight level ranges), with the explicit possibility of using instructions to both aircraft to solve the conflict.

Work Domain Analysis

The results of the work domain analysis are given in an Abstraction Hierarchy. The AH summarizes knowledge on the work domain at different levels of abstraction. At the highest level, labeled "Functional Purpose" in this AH, the goals of the system are identified. The primary goal of air traffic control is to ensure the safety in the air. Only when safety is ensured, the ATCo can devote attention to the next goal, ensuring efficient and orderly flow of traffic (Figure 1). As with previous analyses for this domain, relative locomotion and absolute locomotion are salient functions at the Abstract Function level. A requirement for locomotion is the availability of airspace, and a function that impedes locomotion are dynamic and static obstructions, for example special use airspace, other aircraft or terrain. Although they could be considered as not belonging strictly to the work domain, but rather to be a tool involved in a specific solution, flight plans are included at this level too.

Control Task Analysis

The control task analysis for this system is performed for two different task, one is monitoring and maintaining the safety, corresponding to the first purpose in the AH, and the second is organizing the traffic flow. As a reminder, a skeleton for the decision ladder is given in Figure 2. The different interpretation of the actions in this ladder for the two tasks is given below. First for the safety task:

activate Starts with the recognition that a planned or current path of one or more aircraft will lead to a loss of separation in a short (5 to 10 min) time.

observe Information needs to be obtained about the distance/time to go until the conflict needs to be resolved, tracks of current aircraft in the vicinity, their plans.

identify Determine which aircraft are in conflict. Which aircraft affect or constrain the solution. How large is the conflict is, whether there is free space to solve the conflict, what will be the effect on the current flight plans.

interpret Determine what the disruption of the conflict is. How does it affect operation? What are remaining alternatives.

evaluate Choose the best or an acceptable option.

task definition Given the best possible solution, define what needs to be done to implement it. Which aircraft need to be maneuvered. What monitoring is necessary?

procedure formulation Determine the commands to give. Directions, sizes, new speeds/headings or altitudes.

execution Communicate with the pilots. Implement the solution. Monitor the follow-up.

For efficient flight execution, the stages in the decision ladder can be formulated as follows:

activate Starts with the recognition the planned or current path of one or more aircraft (or even the lack of having a planned path) will not bring the aircraft to its required exit point at the proper altitude.

observe Information needs to be obtained about the desired exit point, tracks of aircraft in the vicinity.

identify Determine the state of the current plan, find a possible path for bringing the aircraft to its exit point, determine whether crossing or competing aircraft form a limitation.

interpret Evaluate possible solutions and their effect on the traffic pattern and safety. Determine where in the sequence to place the current aircraft.

evaluate Choose the best or an acceptable option.

task definition Given the best possible solution, define what needs to be done to implement it. Which aircraft need to be maneuvered. What monitoring is necessary? Somehow store or record the plan.

procedure formulation Determine the commands to give. Directions, sizes, new speeds/headings or altitudes.

task execution Communicate with the pilots. Implement the solution. Monitor the follow-up.

Display Design

Previous conflict resolution displays for aircraft and for air traffic control were based on visualizing the relation between the relative velocity of an intruder (or conversely, the relative velocity towards an intruder) with the absolute velocity of the controlled aircraft itself. The current project has a different aim, in that we would like to use adjustment of the velocity of both aircraft to remove the conflict. The design needs to overcome a number of issues:

- **Control degrees of freedom.** Resolving a conflict in the horizontal plane with instructions to a single aircraft potentially requires two inputs; a new heading and a new speed. Thus, two degrees of freedom in the control vector. The current displays can show this information on a screen. Addition of a third degree, for example altitude control, has been attempted, but this requires the combination of several displays, which brings associated problems with maintaining visual momentum. Defining the four needed control inputs at the same time, i.e. heading change and speed change for the two aircraft, is not feasible. Somehow it should be possible to define a maneuver in which the two aircraft move in two steps.
- **Balanced maneuvering**. A way of reducing the number of degrees that have to be controlled for the two aircraft is by determining how much each of the aircraft contributes to the solution of the conflict. After choosing one of the vectors above, the ATCo has fixed how much of the solution must be provided by each aircraft.

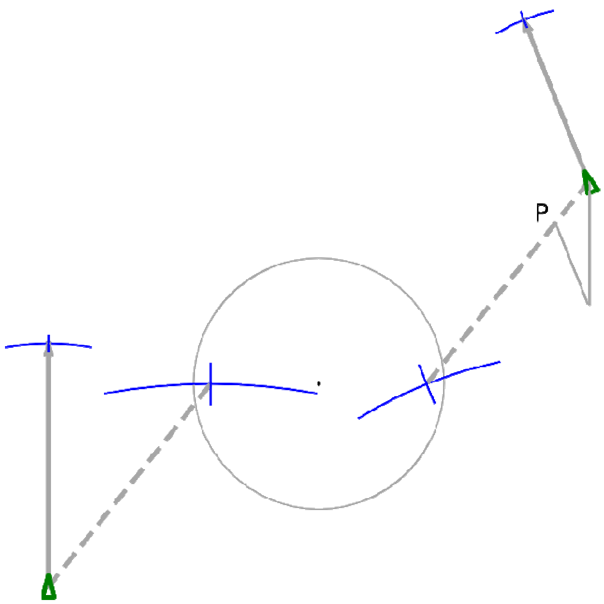

Figure 3: Diagram outlining the geometry in visualizing the conflict with respect to the midpoint between the two aircraft. Point "P", at one fifth of the 300 [s] velocity vector, indicates the relative velocity with a 60 [s] speed vector.

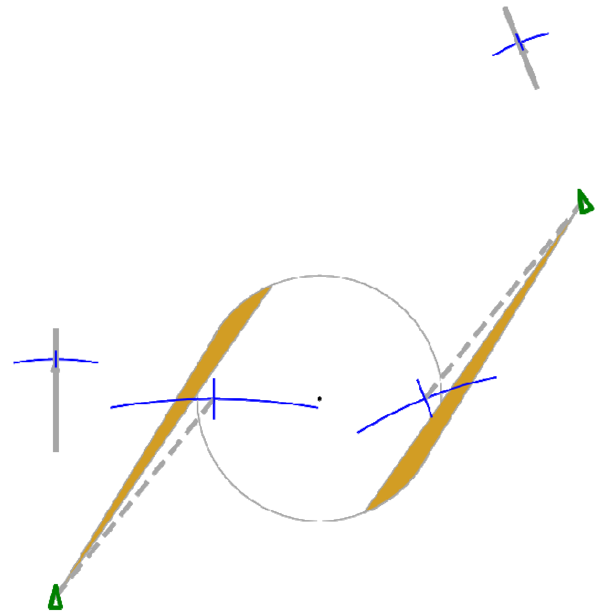

Figure 4: Further visualization of the conflict geometry. Triangular zones have been added, with one side indicating the change in relative velocity needed to solve half of the conflict, and the "outer" side indicating the relative velocity needed to solve the complete conflict.

- **Conflict priority and warning.** The SSD based displays discussed above provide a means to choose headings and speeds that resolve the present conflicts, but by itself the SSD does not aid in the detection of conflicts. To provide that functionality, the aircraft symbols in the plan view may be marked. However, with several marked symbols the task of prioritizing the conflicts still requires the ATCo to scan the different aircraft and call up their SSDs.
- **Traceability across abstraction levels**. The common format for an Air Traffic Display is a plan-view display with symbols representing the aircraft in the sector. Speed vectors or history dots ("breadcrumbs") can provide a velocity overlay. Any additional visualization is preferably traceable to the position and velocity physics of the aircraft, so that its role and effects become predictable and understandable. In other words, visualizations should be linkable to physical actions.

As a first step in the design, the aircraft-centric property of the SSD displays is questioned. The SSD displays provide a visualization of the relationship between the relative velocity and the absolute velocity of one considered aircraft of the aircraft in a conflict.

Instead, as shown in Figure 3, the center of a pair of aircraft that is in conflict (or indeed, any pair of aircraft) can be considered. When taking this midway between the two aircraft a point can considered that is always in the middle of the two aircraft, also when these are at their closest point of approach. The speed of this point is the average (vectorially) of the speeds of the two aircraft. Note that this has some relation to the visualization in (Gaukrodger et al., 2009), although there all conflicts are presented in the same space, making it difficult to relate conflicts to the aircraft involved.

Next, let's consider the relative velocity of the two aircraft with respect to this point. By subtracting the velocity of the midpoint from both aircraft velocities, the relative velocity is obtained. The two relative velocity vectors are parallel (the dotted lines in Figure 3). As was claimed before, the midpoint moves with the pair of aircraft. By considering the relative velocity with respect to the midpoint, one can see that relative position of the two aircraft at closest point of approach, is where a line at the midpoint, perpendicular to the line through the two current aircraft positions, crosses the relative velocity vectors. To have sufficient separation at that point, the distance between the vectors should be larger than the protected zone size, meaning that the relative velocity vectors should stay out of a circle with a diameter of the protected zone size centered on the midpoint, which we will term avoidance zone.

This already gives one option into visualizing the safety goal, see Figure 3. By indicating how much of the circle around the midpoint is clipped by the velocity vectors, or, alternatively, how much intrusion of this circle is present (Figure 4), the distance at closest point of approach is indicated. This visualization has the additional advantage of having a surface area roughly proportional to the severity of the conflict.

The visualization by itself covers detecting the problem, indicating which two aircraft are involved, and providing data for evaluation of safety (activate, observe, identify and part of the data needed for evaluate, Figure 2. However, if we want to use this visualization in an EID interface, we should somehow link the action possibilities, i.e. changing speed and heading of the individual aircraft, to the effects on the clipping of the midpoint circle.

In most cases, and when altitude changes are not applicable, a heading change will be preferred to a speed change. When considering a – possibly combined – heading and or speed change as a change in the aircraft's speed vector, the most efficient coordinated maneuver of the two aircraft, in velocity space, will be perpendicular to the relative velocity with respect to the midpoint. To support the ATCo in deciding on a maneuver, the "common" maneuvering options need to be elaborated somehow in the context of the constraints in the relative velocity space.

Given that the speed of the two aircraft can be represented by vectors v1 and v2 , the speed of the midpoint is simply $\underline{v}_m = (\underline{v}_1 + \underline{v}_2)/2$. The relative velocity of aircraft 1 with respect to the midpoint and its avoidance circle is $\underline{v_{r1} = \frac{1}{2}(v_1 - v_2).}$

Similarly the relative velocity of aircraft 2 can be calculated. However, presenting speed vectors on a plan view display requires a scaling. A feasible "size" for the speed vector is 60 seconds, i.e., the speed of the aircraft is converted into distance by multiplying with 60 seconds and taking that for the speed vector size. For conflict detection and resolution, 60 seconds is too short, commonly 5 minutes is needed, so the relative velocity vector requires a scaling of 300 seconds. If the tip of the relative vector then points into or through the avoidance zone, this then indicates that there will be a loss of separation within 5 minutes.

On the other hand, a fixed scaling with 300 seconds might produced a confusing representation when the relative velocity of the two aircraft is very large, such as with a blunt angle crossing or a head-on conflict. In that case the closest point of approach may be much closer – in time – than five minutes. The visualization of the relative velocity then extends to a point way beyond the closest point of approach, possibly cluttering other parts of the display. The solution proposed for this is limiting the relative velocity vector size to the distance to the midpoint, symbols will have to indicate that the vectors are calculated for a shorter time than 5 minutes.

The scaling does complicate the link to the action possibilities. The easiest way to represent the action options for an aircraft is by expressing them as a change in the aircraft's speed vector. Half of that change carries over to the relative velocity vector (cf. the second equation), but the scaling of the relative velocity vector is – normally – larger than that of the velocity vector, so it carries over to a point closer by, point P in Figure 3.

The aircraft speed is also limited, and this limitation should be discoverable from the interface. To visualize that, the speed vector can be modified to show the range of achievable speeds, and the tip can be replaced by a cross, sized to represent 10 kts speed change (along the vector) and 10 degrees heading change (curved section perpendicular to the vector). To link this scaling to the tip of the relative speed vector, and thus to the separation in relative space, the same cross is repeated at that tip, but magnified to reflect the scaling of the relative velocity vector.

The visualization options for the display have not yet been finalized. Assuming the basic geometry, several options are still open and need to be tested in evaluations. The avoidance circle does not need to be visualized completely, only visualizing the parts of the circle that are cut out by the relative velocity vectors would suffice. This has the additional advantage that the size of the symbology will correspond to the urgency of the problem.

Comparison to Analysis

The avoidance zones in the display will pop up only when a conflict is detected, which means that with current heading and velocity the separation will be lost in 5 minutes. Such behavior adequately supports activation of the task of resolving conflicts and keeping separation. The degree of conflict, and the available means to solve it are visible in the depth of penetration of the conflict zone and the sizes and orientation of the action spaces. The location of the conflict zones also gives information on the aircraft involved in a conflict. Using the double rings, the maneuvering can either be distributed over both aircraft or assigned to a single aircraft. The visualization is most suited to conflict avoidance. Compared to the SSD displays, the visualization of the available action space is missing; with an SSD display, one can choose a "free" heading, with this display one can choose a heading that solves a particular conflict, but whether that heading introduces another conflict is not clear beforehand. This might lead to more exploratory – what if type – use of the interface. As an additional bonus, the gravity of a conflict roughly corresponds to the size of the visualization area, making pressing conflicts inherently more salient.

Conclusion and recommendations

Starting from the principle of visualizing relative velocity, a display presentation for – potentially cooperative – solving of pairwise aircraft conflicts is developed. The presentation supports the operator in several steps outlined in the cognitive task analysis; detection of a conflict (zones come up), and in the collection of information about time to go and involved aircraft. The visualization of "standard" actions helps in defining an avoidance strategy and determining which commands to give. Rather than focusing on a single aircraft to solve a conflict, the visualization focuses on the pair of aircraft in the conflict. Using a double boundary for the conflict solution, one halfway to full separation, and the second indicating full separation, the operator will have a choice to solve a conflict with one or with two aircraft.

In the current design, the functional purpose level, for example by showing where the aircraft should be guided, is not explicitly shown. This information is normally shown as extra information in the aircraft label or in the flight plan, i.e. as symbolic information. Different visualization options can still be explored, and the display needs to be evaluated in simulation. In addition, the vertical dimension needs to be added; even when supporting the current practice in ATC, which is to treat climbing or descending traffic as if it were occupying multiple flight levels, climbs or descents will have a significant influence on the aircraft's speed range.

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References

Abdul Rahman, S. M. B., van Paassen, M. M., & Mulder, M. (2011, August). Using the solution space diagram in measuring the effect of sector complexity during merging scenarios. In Aiaa guidance, navigation and control conference (pp. 1–25). Portland (OR). (AIAA-2011-6693)

Gaukrodger, S., Wong, W., Fields, B., MLoomes, M., Han, F., Mun˜ oz Araco´ n, M., . . . Monteleone, A. (2009, December). The multi-conflict display. In 8th innovative research workshop & exhibition (pp. 93–100). Bretigny, France: EUROCONTROL.

Lodder, J., Comans, J., van Paassen, M. M., & Mulder, M. (2011, April). Altitude-extended solution space diagram for air traffic controllers. In J. Flach, M. Vidulich, & P. Tsang (Eds.), Proceedings of the 16th international symposium on aviation psychology (p. 345-350). Dayton (OH).

Mercado-Velasco, G., Mulder, M., & van Paassen, M. M. (2010, August). Analysis of air traffic controller workload reduction based on the solution space for the merging task. In Aiaa guidance, navigation and control conference (p. 18). Toronto, CA. (AIAA-2010-7541)

Vicente, K. J. (1999). Cognitive work analysis. toward a safe, productive, and healthy computer-based work.Mahwah, NJ: Lawrence Erlbaum Publishers.