Air Traffic Control Interface for Creating 4D Inbound Trajectories

Rolf E. Klomp

M.M. (René) van Paassen

Max Mulder

Mariska I. Roerdink

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Rolf E. Klomp, M. M. (René) van Paassen, Max Mulder
Aerospace Engineering – Delft University of Technology
Delft, The Netherlands

Mariska I. Roerdink
Air Traffic Control The Netherlands (LVNL)
Schiphol-Oost, The Netherlands

It is to be expected that the task of an air traffic controller will change with the introduction of 4D (space and time) trajectories for aircraft. To support this new work, an interface for the manipulation of 4D trajectories has been created. The interface uses a time-space diagram – which shows progress of the aircraft along its planned track, in which conflict zones for conflict with other aircraft are presented, and a vertical path display, which presents the altitude along the planned track. In combination with a traditional plan-view display, and additional elements and tools in the displays to create a visual link between the paths displayed in the three displays, the interface enables the modification of a 4D planned trajectory for inbound aircraft.

An experiment has been performed with a PC-based simulation. Two variants were tested, one in which the aircraft could only be controlled in the current sector, and one in which the speed (but not the path) of aircraft could be modified some time before these aircraft entered the sector; a practice expected to produce improvement of efficiency in small sectors. The results validate that the enhanced interface can be used to manage the air traffic safely and efficiently. It was also shown that the ability to manipulate the speed of an aircraft in the adjacent sector can significantly *increase* situation awareness and *reduce* controller workload.

Introduction

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 (Oprins & Schuver, 2003; Oprins, 2008). In the coming decades, the task of an air traffic controller is predicted to undergo a large transformation. The pull for transformation comes from the increasing demands which are placed on the air traffic management (ATM)-system (Dlugi et al., 2007, 2008; Anon., 2007). A push is provided by technological advances on the air- and ground side of the ATM-system, which make a new form of air traffic control (ATC) possible (Slattery, 1996; Ballin, Hoekstra, Wing, & Lohr, 2002). This is expected to result in a situation where 4D (space + time) trajectories stored in automated support tools form the basis for the ATCo's work (Whiteley & Wilson, 1999; Jorna, Pavet, Van Blanken, & Pichancourt, 1999; Heesbeen, Hoekstra, & Valenti Clari, 2003; Prevot, Lee, Smith, & Palmer, 2005).

In a previous project (van Dijk, van Paassen, Mulder, & Roerdink, 2009), a human-machine interface (HMI) has been developed to visualize these 4DT's and support the air traffic controller in planning and managing the air traffic in this future situation. An initial validation experiment with this interface showed ATCo could safely and efficiently manage air traffic, however, a number of areas for improvement were identified. This paper describes the re-design and validation of the interface. The option to manipulate the vertical path of the aircraft has been added, and visual links between the different views presented to the ATCo were created.

Operational Concept

The interface is designed for a situation where the path of aircraft is define by means of 4D trajectories (Ballin et al., 2002; Wichman, Lindberg, Kilchert, & Bleeker, 2004), and it focuses on control in the CTA (Controlled Terminal Area) sector. The CTA is an air traffic zone where most traffic either comes from upper airspace or neighboring CTA's and enters the TMA (Terminal Maneuvering Area) around an airport, or vice versa, and control there is supplied by the Area Control Center (ACC). It is expected that instead of the tactical control performed today, where an ATCo shapes the aircraft's trajectory by issuing speed and heading instructions, the future ATC work will involve more strategic control, and a large part of the ATCo's task will be to create and define conflict-free trajectories *before* aircraft enter the CTA. It is also assumed that in the future, traffic in the TMA will largely follow fixed routes to the runway, to enable aircraft to perform low-noise continuous descent approaches (Wubben &

Busink, 2000; Meijer, de Gelder, Mulder, van Paassen, & in 't Veld, 2009). To make that possible, the timing of the aircraft entering the TMA has to be adjusted in the CTA.

As aircraft enter the radar screen and the ACC control system, the initial planned trajectory runs from the entry in the ACC straight to the intended entry point for the TMA. Such a path might have conflicts with aircraft currently in the ACC, and the time of arrival in the TMA might not be correct yet. The ATCo responsible for the ACC will have to create a 4DT that ensures the timing of arrival in the TMA is correct, and that is free from conflicts with traffic in the ACC. In our set-up the ACC is modeled after a Schiphol ACC and two entry gates to the TMA are used, see Figure 1. The schedules for the two entry points to the TMA are linked; the use of a single runway is assumed, and the aircraft have to enter the TMA such that separation at the runway threshold is achieved. The path length in the TMA is different for the two entry points, and when a change in entry point is selected a different entry time is required. In many cases, the size of the ACC airspace (in many places in Europe and on the US West Coast) limits the options for correcting the timing of an arriving flight. One optional extension considered is the possibility to control speed of aircraft still in neighboring sectors.

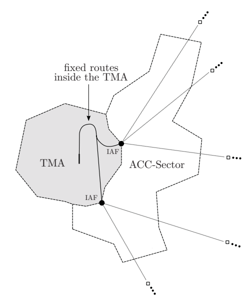


Figure 1: Three-dimensional fixed routes inside the TMA, starting at the Initial Approach Fixes. Outside the TMA, aircraft arrive from all directions and are merged by ACC ATCo.

Display Design

The display is a further development of a display used in a previous project(van Dijk et al., 2009). The design is focused on presenting the constraints of the work domain – i.e. planning and de-conflicting 4D trajectories and planning the arrival sequence for the TMA.

The planning interface is formed by a time-space diagram (TSD), which displays the planned times versus the along-track distance of an aircrafts 4DT, (1) in Figure 2. The time-space diagram is linked to a display of the inbound traffic sequence, bars linked to each aircraft's arrival time represent wake vortex separation minima, by "stacking up" the bars – indirectly, through speed and path changes – the correct entry times into the TMA are achieved. For the aircraft currently selected, the TSD provides a display of conflict areas, which corresponds to coloring of the ground track in the plan view display (PVD) when the track is crossed by other aircraft. In one of the display configurations, a time slider is added to the TSD. This slider can be used to display "ghost positions" for the aircraft in the system on all three views, visualizing the temporal development of the traffic pattern. Below the TSD, a vertical situation diagram (VSD) shows the vertical track, again against the planned ground track. The VSD shows where other aircraft cross the planned trajectory. For a selected aircraft, potential conflict areas will also be shown. In this way constraints on vertical maneuvers (in the VSD) or on velocity maneuvers (in the TSD) can be seen in the display. The linked combination of these two displays forms the Time-Space and Vertical Display (TSVD). The visualization of conflict with other aircraft support part of the ATCo's task, namely the de-confliction of the 4DT. To support the planning of arrival times to the TMA, additional visualization has been added to the TSVD. Given constraints on speed instructions, an arrival range prediction can be calculated for a selected aircraft. The prediction shows the fastest and the slowest possible flight, given that the lateral path is not changed.

Evaluation

With the PC-based implementation of the TSVD, an experimental validation has been performed to answer the following questions:

- Does the addition of the new tools (conflict visualization on the PVD, the ghost view tool) improve situation awareness and reduce controller workload?
- What is the effect of the possibility to plan speed changes for aircraft still in a neighboring sector; while the lateral path there is fixed (under the responsibility of the ATCo of the other sector), a speed change may be instructed.

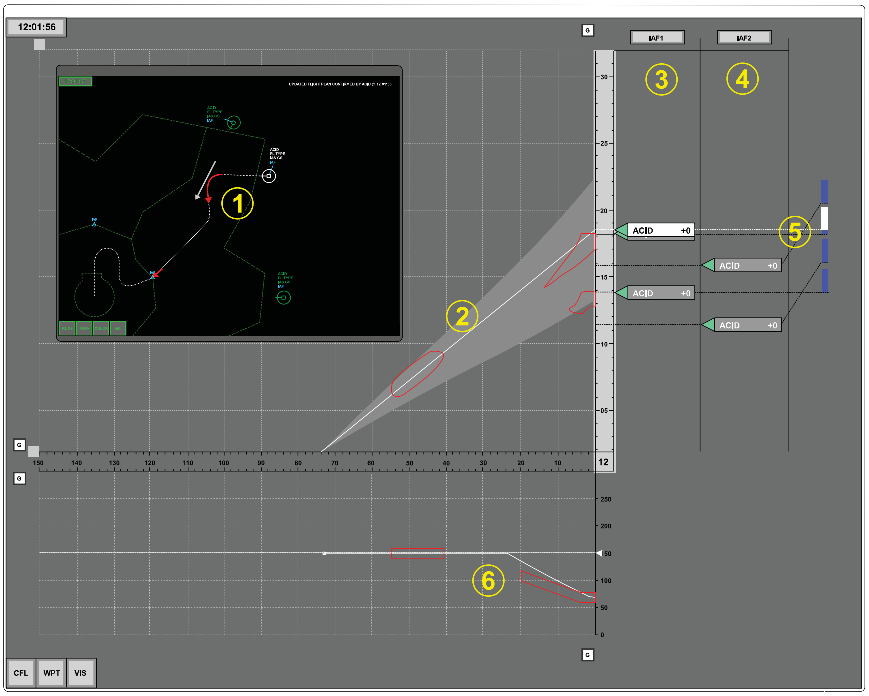


Figure 2: TSVD when an aircraft is selected

1 Conflict zone in PVD with part of track of conflicting aircraft
2 Conflict zones in TSD
3 Arrival list for entry point IAF1
4 Arrival list for entry point IAF2
5 Arrival sequence planning, horizontal bars are for IAF1, slanted bars represent extra travel time for aircraft arriving at IAF2
6 Conflict zones in VSD
7 Range of possible arrival/travel times for selected aircraft (light grey zone)

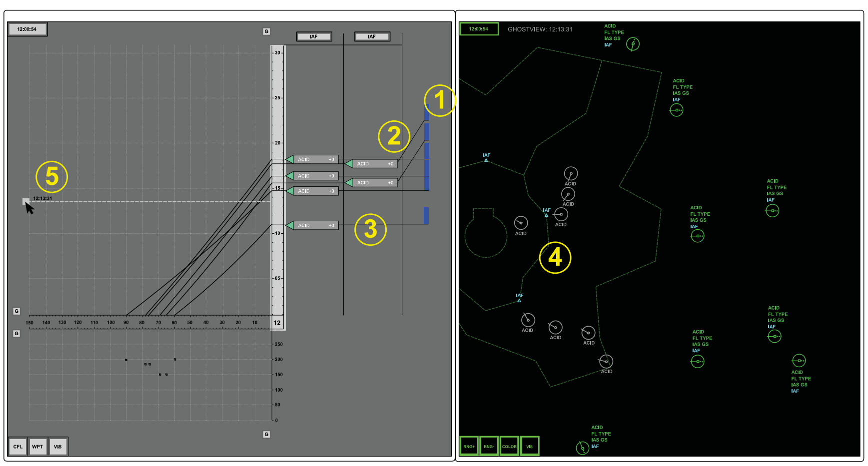


Figure 3: TSVD and PVD when no aircraft is selected, with the ghost view tool active

1 Wake vortex separation bars (blue)
2 Additional travel time for aircraft arriving at IAF2
3 No additional travel time for aircraft arriving at IAF1
4 Ghost images for the aircraft in the PVD
5 Ghost slider, positioned at a future time

Four different scenarios, with different traffic of approximately equal difficulty were used. Three types of aircraft were simulated in clean configuration, each with different performance characteristics which influence the feasible range of 4DTs: The Airbus A319-114, the Airbus A330-301 and the Airbus A340-313. The Eurocontrol GAME (Anon., 2009, 2002) aircraft performance model has been used to calculate the relevant elements of aircraft performance such as minimum/maximum speed and idle rate of descent. Aircraft entered the controlled sector between FL120 and FL230, with an Indicated Air Speed (IAS) varying between 220kts and 280kts, and were given an initial 4DT leading to one of two Initial Approach Fixes (IAFs). For reasons of simplification, a fixed turn radius of 5NM has been assumed, and the fixed minimum landing interval between two aircraft (length of the 'blue bars') has been set to 1.7 minutes for all aircraft. The initial conditions were set such that at a certain point the TMA would become congested and the subject would have to issue changes to the 4DTs to maintain a safe and efficient sequence of aircraft.

Twelve subjects participated in the experiment. The subjects were either active ATCo, retired ATCo, or researchers with initial training in air traffic control. Two independent variables were varied, *TOOLS:* The possibility to use the ghost view tool and the conflict visualization on the PVD was switched on (T_E) and off(T_D) and *SECTOR:*

The possibility to issue speed requests to aircraft in the adjacent sector was enabled (S_E) or disabled (S_D). The four resulting conditions were combined with the scenarios in a latin square design. The following dependent measures were used to analyze and compare the four conditions:

Loss of separation Loss of separation was measured by logging the number of separation violations between aircraft. For the experiment, the minimum separation criteria were set to 5NM horizontally and 1,000ft vertically.

Workload The controller workload was measured by using a digital version of the NASA-Task Load Index (NASA-TLX (Hart & Staveland, 1988)) subjective mental workload questionnaire. The TLX-questionnaire returns a score ranging between 0 and 100. Here, a higher score indicates a higher workload.

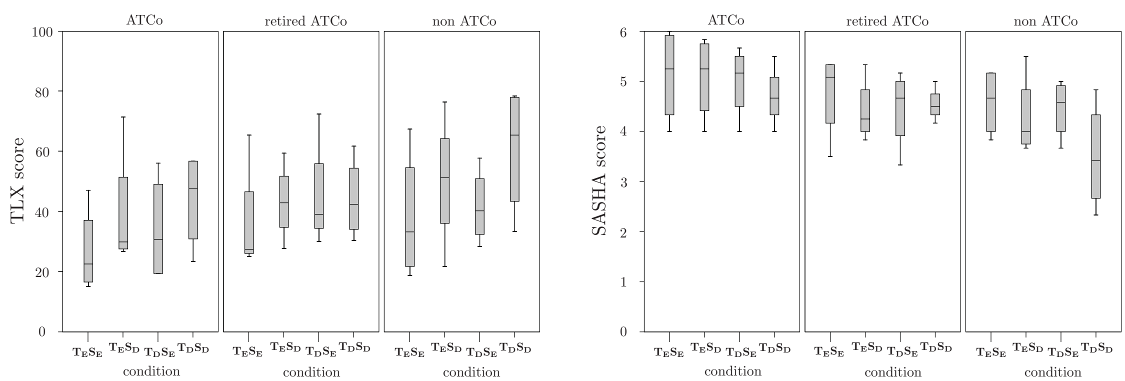
Situation Awareness The controller situation awareness was measured using the Eurocontrol SASHA (Straeter, Woldring, Barbarino, Skoniezki, & Philipp, 2003) questionnaire, which provides an overall subjective score for SA. The scores range between 0 and 6. A higher score indicates a higher (better) level of SA.

Experiment Results

Loss of separation. An analysis of all aircraft trajectories showed that no loss of separation occurred in the experiment.

Workload. Figure 4(a) shows a boxplot of the measured TLX scores per condition, and per subject group. Using a Kolmogorov-Smirnov test, the TLX data were found to be normally distributed ($D(48) = 0.120$, $p > .05$). A repeated-measures Analysis of Variance (ANOVA) of the TLX scores showed that the between-group effect was not significant ($F(2,9) = 0.627$, $p = 0.56$). Therefore, the within-subject effects due to the TOOLS and SECTOR option have been tested for all participants combined.

The TOOLS variable did not have a significant effect on measured TLX ($F(1,9) = 1.760$, $p = 0.17$). The SECTOR variable did have a significant effect ($F(1,9) = 11.087$, $p < 0.01$). Enabling speed control over aircraft in the neighboring sector significantly reduces workload.



(a) Boxplot of the measured TLX scores (b) Boxplot of the measured SASHA scores

Figure 4: Boxplots of the measured NASA-TLX and SASHA scores per condition, clustered per subject group

Figure 4(b) shows a boxplot of the measured overall SASHA scores. The figure shows that the ATCo group rate their situation awareness the highest (closest to the maximum score of six), and the non ATCo group the lowest. Furthermore, the figure shows that most situation awareness scores are located in the higher range of the scale. A Kolmogorov-Smirnov test was performed, and showed that the measured SASHA data were normally distributed ($D(48) = 0.085$, $p > .05$). Again, no significant between-group effect was found by using a repeated-measures ANOVA of the SASHA scores ($F(2,9) = 1.439$, $p = 0.29$). By evaluating the within-subject effects of all participants combined, no significant increase of situation awareness was found for the conditions with the TOOLS enabled compared to the conditions with the TOOLS disabled ($F(1,9) = 3.416$, $p = 0.098$). However, situation awareness was significantly higher for the conditions with the SECTOR option enabled, compared to the conditions with the SECTOR option disabled ($F(1,9) = 6.153$, $p < 0.05$).

Conclusion

Experimental results show that the TSVD can support an ATCo in the new task of planning inbound 4D trajectories safely and efficiently. No loss of separation has been recorded. The addition of two new tools to the interface did not show significant effects on measured situation awareness and workload. Participants did like the option to dynamically project the time-evolution of the planned future traffic situation on the PVD (ghost view tool). The importance of multi-sector coordination and the size of the controlled sector has been underlined by the significant increase of situation awareness and decrease of controller workload, which has been measured for conditions in which speed changes could already be issued to aircraft in the adjacent sector. However, this option would require that the responsibility for these aircraft is to be shared by the two adjacent sectors.

For further development of the TSVD, it is recommended to investigate the form in which outbound and transit aircraft could be incorporated. The TMA planning (blue bars) should also be improved, making it more apparent where merge problems will occur. Furthermore, when no aircraft is selected, cues should be given for the existence and the priority of conflicts. When manipulating the horizontal path of an aircraft, forbidden areas could be indicated on the PVD in which it is unsafe to reroute, although this visualization is expected to require considerable calculation. Disturbances such as wind, bad weather, inaccuracies in trajectory prediction and other unforeseen events were not included in this experiment. These will have to be taken into account when calculating trajectory predictions. The size of the controlled sector has been shown to have significant influence on controller workload, situation awareness and to the efficiency of the traffic flow, but was not taken as an explicit experiment variable. Therefore, further research is required to determine this relationship. Finally, the TSVD is based upon a mature state of four-dimensional operations in which all aircraft have full 4D capabilities. In order to gain operational acceptance, solutions should be found for a transition period in which both the air- and ground segment are only partially equipped.

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