

4D TRAJECTORY MANAGEMENT SUPPORT IN THE C-SHARE PROJECT

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Keywords: *ATM 4DT controller support automation*

Abstract

Within the SESAR WP-E C-SHARE project a novel representation of the tactical and strategical parts of the Air Traffic Management system has been developed. The rationale behind the project is that in the (near) future a number of developments are expected in the air traffic management system that require the role of the controller to evolve towards an operation in a 4D environment.

The main focus of the project was to create a shared mental model between controller and automation that results into a seamless cooperation between human and automation. One of the focal points to achieve this goal was an advisory system that supports controllers in management of perturbation of trajectories while remaining in full control. The system has been tested in human-in-the-loop experiments which show that this type of automation can be a major step in the development of a future ATM support system.

1 Introduction

A key pillar within SESAR is the introduction of Trajectory Based Operations (TBO) as a means for strategic management rather than the current tactical (hands-on) method of control. A central role is foreseen for the human operator, but SESAR also leans heavily upon the introduction of higher levels of automation and advanced automated support tools.

Although the introduction of higher levels of automation is not good or bad in itself, in other complex socio-technical domains this has shown

to often introduce new problems. Examples are coordination breakdowns, skill degradation, over reliance, lack of trust, transient workload peaks, etcetera. In order to mitigate the risk for these so-called “automation surprises” or “ironies of automation”, it is essential to support joint-human automation cognition in future air traffic management systems, by design.

Under the umbrella of SESAR’s WP-E work package, the Technical University of Delft, Thales Nederland and the National Aerospace Laboratory have teamed up to jointly execute the C-SHARE project [11]. The tools developed and tested in the C-SHARE project act as a novel interface for a 4D environment. As the cooperation between controller and automation will be intensified, the key innovation is the introduction of a shared model between humans and automation which is crucial for the controllers situation awareness and trust in and acceptance of the automation.

The development and implementation of the JCS was the main result of C-SHARE. The JCS provides an advanced display and automation tool that aids the controller in providing 4D based air traffic navigation services. The support that the automation provides is such that the controller does not need to adapt his mental model to the model of the automation. The output of the automation rather fits seamlessly in the model used by the controller. It is subtle in the sense that it is not enforced on the controller but is always available as an option.

The results of C-SHARE rest on three pillars. The first pillar of the outcomes has been the “shared representation” of in-flight trajectory ma-

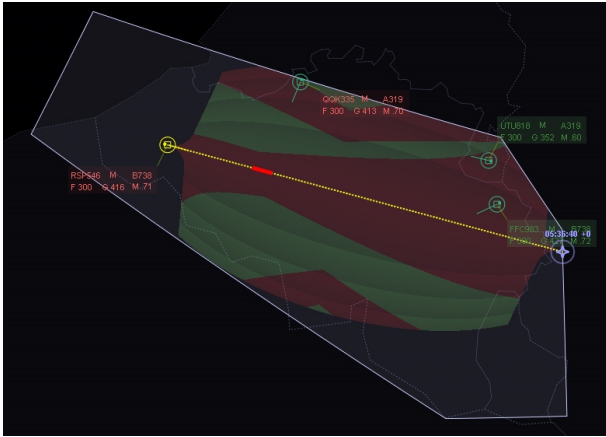


Fig. 1 Example of the travel space. Green areas represent safe areas to add a waypoint, red areas show non-safe areas.

nipulation by ATC. This so-called “Travel Space” representation describes a full set of re-routing possibilities for individual flights, based upon aircraft performance constraints (i.e., turn radius and speed envelope), relative locomotion with respect to other airspace users, and time-based constraints acting on the aircraft business trajectory (see Fig. 1 for an example). The elements represented in the Travel Space follow directly from the constraints which arise from the work domain, independent of who will act on the control task, the human, the automation, or both.

The second pillar consists of an automated conflict resolution advisory algorithm. When workload increases, controllers can request advisories from this system to quickly generate valid and logical solutions. For advisories to be interpreted efficiently by the controller it is necessary that the resolutions fit the mental model of the controller. It has been shown in previous studies that transferring control and sharing decision making with an automated agent requires that the advisory heavily portrays what is considered a human operator’s strategy of perturbation management (e.g., strategic conformance) [13]. In this way the operator can understand and feel that they are in the loop, although parts of the problem-solving process might be externalized and executed by the automation. Therefore, the JCS advisory algorithm has certain advanced properties that together ensure that advised solu-

tions seamlessly fit the mental model of the controller. As a result, advisories can be quickly interpreted and a decision to effectuate them can be made efficiently.

The final pillar is formed by the Human Machine Interface (HMI) with the controller that consists of a graphical representation of the Travel Space and a mouse driven interaction model.

A series of human-in-the-loop experiments with a software-based implementation of the JCS served to validate and evaluate joint human-automation performance with such a system.

The scenario chosen for the C-SHARE project is that of a large en-route sector in which aircraft fly a pre-planned 4D trajectory. Because of the current state of the JCS, solutions are currently limited to 2D+time (resulting in a lateral solution plus speed constraint) but can be easily extended to include altitude.

This paper focuses on the automation part of the JCS, the optimizations and the presentation to the controller. Details about the Travel Space of the JCS can be found in [12]

2 Perturbation management

In an ideal 4DT environment no ATC is necessary because all aircraft precisely follow their de-conflicted trajectory that was created in an early stage. Although modern aircraft are very well capable of flying a 4D trajectory, possible *perturbations* of these 4D trajectories will make it necessary to keep controllers fully in the loop to be able to intervene when necessary. As perturbations of one aircraft (and therefore a deviation from its 4D trajectory) may have *emergent* effect on the network as a whole, the JCS aims to deal with these perturbations such that at sector exit the aircraft has resumed its 4D trajectory. This ensures that perturbations will not have emergent effects outside the sector. While perturbations of 4D trajectories may have many causes, they all have the result that previously de-conflicted 4D trajectories may no longer be de-conflicted. Appropriate controller action is necessary to ensure conflicts are prevented and the aircraft is able to resume its

4D trajectory. Causes for perturbations include:

- (unexpected) weather, closed airspace etc.;
- deviations of sensors (e.g. GPS);
- emergencies;
- technical problems (on-board, but also support systems on the ground);
- other delays.

A challenging example of a large perturbation is the unexpected introduction of a restricted airspace (RA). Such a RA may be a thunderstorm or a temporarily closed airport. Either way, when the 4D trajectories of the aircraft were generated, the RA was not known rendering many 4D trajectories invalid. When this happens, appropriate controller action is necessary to ensure aircraft avoid the RA while still maintaining a stable 4D network.

Because of the wide range of potential perturbations and their complex impact, the role of an Air Traffic Controller (ATCo) remains indispensable. This is also in line with SESAR in which the ATCo remains to play a key role in the ATM system.

Recovery from a perturbation requires improvisation and the ability to quickly improvise; a controller therefore needs to be actively in the loop. If the amount of automated support increases to a level at which a human is no longer able to oversee the whole picture, it is not possible to quickly intervene in case of a perturbation. Therefore, within the C-SHARE project the automation *supports* the controller in its task to stay in full control.

2.1 Previous work

Algorithms to inform, support or even to replace ATCo's have been in development for some decades. A broad set of methods has been proposed all with their own specifics. In addition, airborne algorithms have been developed to support e.g. free flight. Traffic Alert and Collision Avoidance System (TCAS) is one such example of an airborne system. It has been proven to be

successful to prevent short term conflicts by providing a (sometimes coordinated) solution.

Other Collision Detection and Resolution (CD&R) algorithms can be classified based on several properties. In [1] a framework is proposed to categorize the different CD&R algorithms. This work provides an extensive overview of CD&R algorithms up to the start of this millennium. 6 key design factors are used for categorization. These include type of state propagation, number of state dimensions, use of a clear conflict definition, resolution method, number of dimensions of resolution maneuvers and finally the ability to handle situations with multiple conflicts.

Algorithms can also be classified based on their resolution method. *Simple algorithms* use a prescribed maneuver based on current conditions. These methods are usually limited in their use to specific situations (see for example [4]). *Genetic algorithms* use fitness functions to quickly evaluate many generations of (mutated) solutions [2, 7, 8]. The idea is that each generations creates better (i.e. fitter) solutions. After a number of generations, the most fit solution is selected. *Force field* approaches use attractive and repulsive forces to define maneuvers for conflict avoidance [3].

Conflict resolution in ATM is a problem that is closely related to (dynamic) motion planning, a problem which has been shown to be NP-hard [6]. Many (non-complete) geometric approaches have been proposed. In [5] the authors propose a discretized method that generates a feasible set of "tubes" by using a graph search. The tubes can then be used to generate conflict free solutions. A multi-agent approach is described in [9]. It calculates sets of feasible maneuvers that guarantee maximal safety under uncertainty. More recent results include [10] in which the type of conflict is detected and an preferred resolution is generated. The preferred resolution maneuvers are listed in a table and iteratively tried.

2.2 (Quality) Criteria

Although some current algorithms used input from ATCo's to design their methods, most al-

gorithms are not designed for collaboration with controllers. They usually aim to either replace controllers or generate better solutions than a controller would. This approach is not in line with the philosophy of the C-SHARE project. In C-SHARE, the seamless collaboration of controller and automation is a central pillar. During the iterative development of the JCS, a set of requirements has been created for the resolution generation algorithm to achieve such seamless collaboration.

The resolutions generated by the C-SHARE algorithm will be presented to the controller as advisories to solve a conflict. When a conflict has been detected, this is shown in the HMI of the JCS by making the associated aircraft labels red. It is then up to the controller to solve the conflict. To ensure that a perturbation of one or more aircraft does not have a huge emergent effect on the 4DT system as a whole, it is preferred that the aircraft are back on their originally planned 4D trajectories before leaving the sector (in addition to vectoring, often a speed change is necessary to achieve this). If this is not possible there are two options: request a revised 4D trajectory or let the downstream sector solve the conflict. The latter requires additional coordination. Within the C-SHARE projects and its evaluation sessions, conflicts were always solved before sector exit.

A controller can take the initiative to request a resolution from the automation. This request is done by selecting an option from the aircraft pull-down menu. This implies that a resolution has to be generated very quickly to ensure proper HMI responsiveness. Earlier research suggests that a resolution has to be generated within a second to feel “responsive”.

Before a resolution is even considered for display to the controller it needs to fulfill certain criteria. First the solution needs to be conflict free; the resulting 4D trajectory should never lead to a new conflict with any of the existing 4D trajectories.

Resolutions should also not extend outside the current sector. The C-SHARE scenarios consist of en-route traffic. Often these travel in a straight line through a sector. Changing its 4DT will extend the lateral length of the trajectory. To

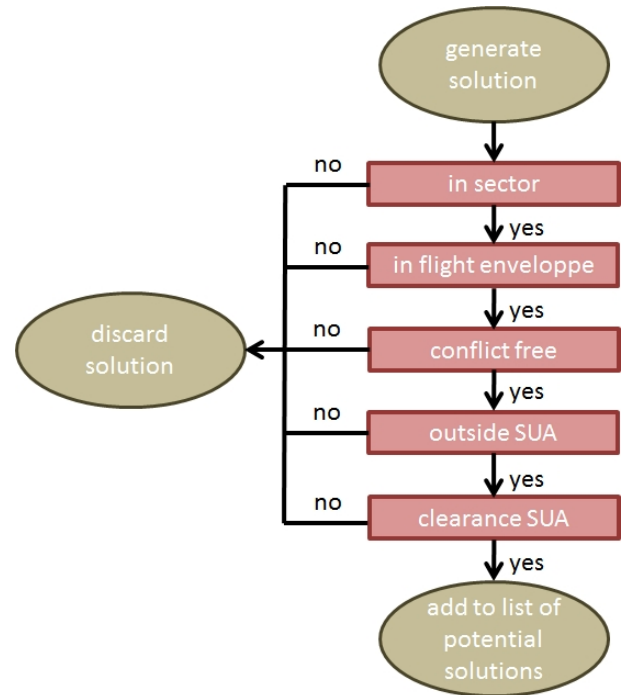


Fig. 2 Schematic view of the planning system

resume the original 4DT at sector exit, the aircraft needs to temporarily increase speed. Obviously this speed needs to be within the flight envelope.

If restricted airspace is active, a trajectory may not travel through it and (from a safety perspective) needs to remain some clearance from it. If a trajectory fulfills all these criteria it is provisionally accepted and added to a long-list. Figure 2 shows the decision chain to accept solutions for the long list.

After generating the list of potential resolutions they are ranked according to an individual quality score that is based on the line of reasoning of an ATCo. To fit the mental model of the controller, resolutions cannot be too complex. Often automated resolution algorithms create resolutions that may be very efficient (e.g. from a fuel perspective) but are very complex (e.g. requiring multiple heading, speed or altitude changes). For a controller to quickly map its mental model on the advisories, the resolution needs to be simple to understand and in line with its own resolution strategies. To summarize, the following elements play a role in the ranking of resolutions:

- complexity of the resolution;

- distance between consecutive waypoints;
- the angle between two segments of the resolution (formed by a list of three waypoints) should be sufficiently large;
- aircraft should not cross in front of each other;
- even if two aircraft have conflict free trajectories, there should never be a (temporary) situation in which the aircraft fly on a head-on course;
- when maneuvering around a restricted airspace, aircraft flying in the same direction should follow a similar path. In practice this means that all aircraft fly either clockwise (CW) or counter clockwise (CCW) around an RA.

To further optimize the communication between human and automation, resolutions will take the form of a (small) list of 4D waypoints. The first waypoint is the current position of an aircraft. The last waypoint ensures that the aircraft is returned to its original 4D trajectory. Details about the resolution ranking system can be found in Sec. 3.3.

As each controller has its own strategy and different controllers may have different approaches to the same type of conflict, it may be that the resolution still does not fit the mental model of the controller. In that case, the controller is able to cycle through a small list of advisories to select an alternative. These alternatives will need to be available instantly. As similar resolutions will still not fit this controllers mental model, it is important that alternative resolutions differ “sufficiently” from each other.

3 Detect and avoid

The detect and avoid module forms the hearth of the automation system. Conflict detection is used to support the controller in its task of identifying aircraft that deviate from their planned 4DT resulting in a potentially dangerous situation. After

a potential conflict has been detected, it is up to the controller to solve the situation. Within this process the controller is able to use the resolution advisories.

3.1 Conflict detection

Periodically, the JCS system initiates a conflict detection procedure that runs in the background. The 4DT environment has resulted in a system with de-conflicted trajectories. For aircraft that deviate from their intended 4D trajectory, the (ground based) detection system may receive an update from the aircraft with new intent. If a deviation is detected without an updated intent, then the flights trajectory is extrapolated to detect any potential conflicts (this makes the conflict detection independent of the aircraft intent).

For each dimension, the minimum distance to each 4DT in the sector is calculated and checked with the minimum separation criteria (recall that the current version of the JCS ignores the altitude dimension). The first position an aircraft comes in conflict is called p_s , the last moment it is in conflict is called p_e . p_s is found by taking small steps from the aircraft’s current position (only conflicts within the current sector are assessed). p_e is found by stepping back from (estimated) sector exit until a conflict is found. This point is called p_e . If an aircraft is involved in multiple conflicts, p_s and p_e will refer to different conflicts.

To minimize false positives, the Base of Aircraft Data (BADA) is used to ensure realistic Flight Management System (FMS) tracks. For each potential conflict, the detect module reports the pairs of call signs involved including p_s and p_e . The HMI then flags these conflicts by coloring the aircraft labels of the involved aircraft red. As the ATCo’s are in full control it is up to them to decide how to solve the conflict. They have the choice to solve the conflict by themselves or to request system support.

3.2 Resolution generation

The conflict resolution algorithm has the task to generate a long list of potential resolutions that do not violate the requirements of the previous

section (shown in Fig. 2). A reverse approach is used to generate these resolutions. Instead of generating a new trajectory between current position of the aircraft and some goal position, the *current* 4D trajectory (which is in conflict) is used as starting point and manipulated until a conflict free resolution has been found. The idea behind this is that the original trajectory represents an acceptable trajectory from ATC perspective. This trajectory provides a good starting point to generate resolutions that fit the mental model of the controller.

The current trajectory contains at least one conflict. The first and last points the aircraft is in conflict are calculated. These conflict start (p_s) and conflict end points (p_e) serve as measure for the conflict resolution algorithm. If the distance between p_s and p_e is large, then also the solution search space should be large. If it is small, the solution space can also be small. The idea behind this is that if a conflict occurs for a longer time, it may need a larger correction.

In Fig. 3a, a sector is shown with two en-route trajectories for AC1 and AC2. The 4DT system ensured that these were de-conflicted in time so that their trajectories can cross without conflict (Fig. 3b). If one of the aircraft is delayed, their crossing paths may cause a conflict. This is depicted in Fig. 3c which also shows the positions of p_s and p_e . A solution area is created that serves as a guidance for resolution generation (Fig. 3d). The center of the solution area is defined by the center position between p_s and p_e . Here, the radius of the solution area is equal to the distance between p_s and p_e .

The original trajectory of AC1 was defined by its sector entry point p_{entry}^1 and exit point p_{exit}^1 . The conflict center $p_{conflict}$ is a point on this trajectory and is located in the center of the solution area. Now $p_{conflict}$ is randomly manipulated to create a new waypoint p_{new}^1 which is inside the solution area (Fig. 3e). A candidate solution is now formed by the trajectory $\{p_{entry}^1, p_{new}^1, p_{exit}^1\}$ (Fig. 3f). As the waypoints are 4 dimensional points, also a time at p_{new}^1 needs to be calculated. A constant speed is assumed along the new tra-

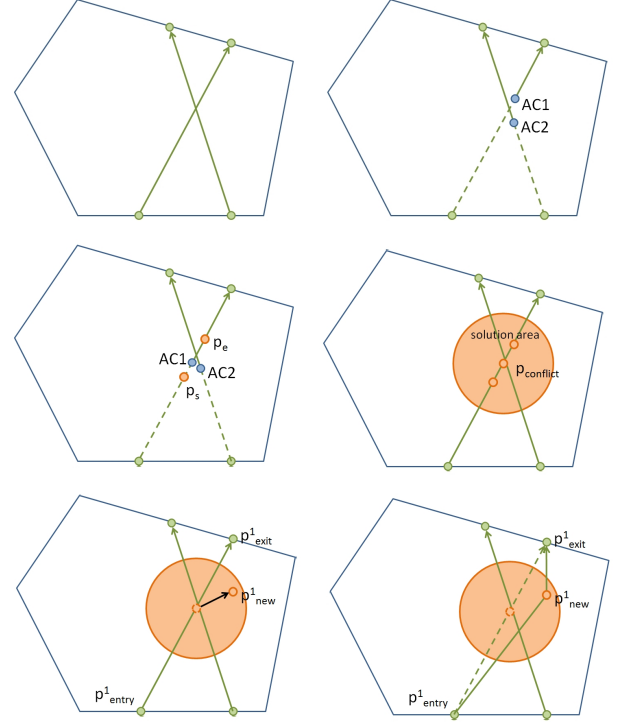


Fig. 3 (a...f) Resolution generation process

jectory where the time at p_{exit}^1 remains equal to the original time (to ensure that at sector exit the 4DT is resumed).

With this technique the time an aircraft has to return to its 4DT is maximized (using the whole sector) increasing the probability that a valid solution will be found. The Base of Aircraft Data (BADA) is used to verify if the new trajectory fits within the flight envelope. A conflict checking module then checks whether the new trajectory is conflict free. All available information about the aircraft can be used in this process (e.g. weight or even airline preference). The new trajectory should solve the current conflicts and not introduce any new conflicts. If not, the trajectory is rejected. Finally, it is verified if the new trajectory has sufficient clearance with restricted airspaces that may be defined (e.g. adverse weather or a closed airspace). If all is well, the trajectory is added to the long list of candidate resolutions.

The above procedure is repeated for a limited amount of time (to ensure responsiveness). Because of the simplicity of the method, the result is still a large amount of potential, conflict free solutions (i.e. >100).

If a large amount of the attempts fail, more complex solutions can be easily generated by creating additional p_{new}^1 waypoints using the same technique. If two such waypoints are created (p_{new1}^1 and p_{new2}^1), the new trajectory is formed by $\{p_{entry}^1, p_{new1}^1, p_{new2}^1, p_{exit}^1\}$ (note that the order of p_{new1}^1 and p_{new2}^1 can be swapped if the latter is closer to p_{entry}^1). These more complex solutions can be threatened exactly like the simpler solutions in the remaining process.

3.3 Resolution Selection

Having the long list of solutions, quality criteria are used to rank them. The quality of a solution is defined by how well a trajectory fits the shared model. In the iterative process of the JCS development, these criteria have been constantly adjusted to (controller) feedback. In the final version of the JCS the following criteria play a role in defining the quality of a solution:

- the (controller) preferred way to let aircraft pass each other (e.g. do not cross in front of an aircraft);
- in case of a RA: let aircraft traveling in opposite directions pass the RA on opposite sides, this creates separated streams of traffic;
- length of the trajectory (related to efficiency);
- length of each individual leg (related to controllability);
- the angle between two legs;
- complexity of the solution.

3.3.1 Length and Angle of the Trajectory

Initial trajectories usually consist of straight paths from sector entry to sector exit. If the automation adds a single waypoint, the resulting solution consists of two legs and three waypoints. To ensure efficient solutions, very short legs (Fig. 4a) and legs with a small angle between them (Fig. 4b) are not preferred. Total resolution length also plays a role.

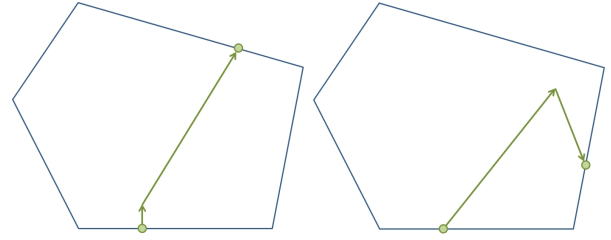


Fig. 4 (a) A resolution with a short leg. (b) A resolution with a small angle.

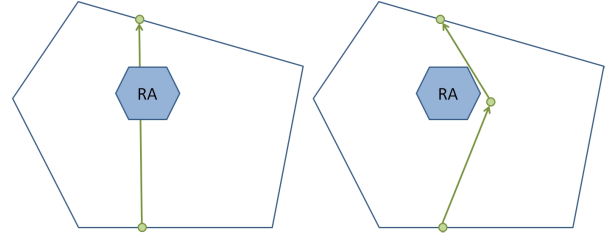


Fig. 5 (a) A 4DT intersects with a RA. (b) A solution that travels CCW around the RA.

3.3.2 Restricted Areas

The automation deals with the RA as it does with other potential conflicts. Its output ensures that RA's are avoided (Fig. 5). In addition controllers apply specific criteria when guiding aircraft around an RA. They often let aircraft go either clockwise or counter-clockwise around an RA to create equal streams of traffic and to avoid the creation of potentially dangerous situations. This may lead to less efficient trajectories but fits the mental model of the controller better. It may even result in a situations in which aircraft that are conflict free are diverted to better fit the general traffic picture (Fig. 6)

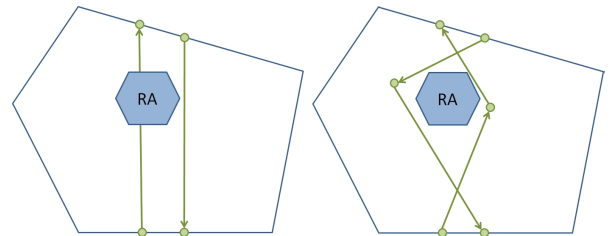


Fig. 6 (a) Only the left 4DT intersects with the RA. (b) Controllers often divert both aircraft to ensure all aircraft travel in the same direction around the RA.

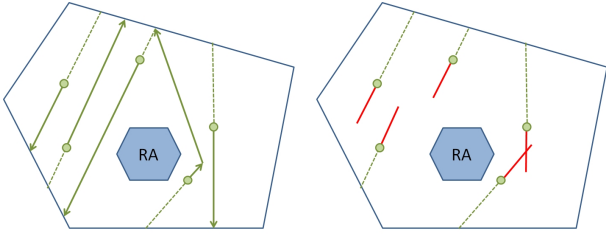


Fig. 7 Although the resolution around the RA seems acceptable (a), the aircraft enter a head-on situation somewhere during the solution (b).

3.3.3 Head-on and Crossing in Front

A controller will never set two aircraft on a head-on course even though they may still have sufficient distance between them. The rationale behind this is that if something goes wrong (e.g. contact is lost) the aircraft may continue their course and enter a state of conflict. By extending an aircraft course, it is verified if somewhere in the solution aircraft have a head-on course. Fig. 7a shows an example of such resolution. The course around the RA seems acceptable but a part of the resolution implies a head-on course with another aircraft.

Algorithmically, the calculation is done by extending the flight path from the current position of an aircraft. We then have a line that moves in front of the aircraft (a so-called look-ahead line). The length of this extension in the C-SHARE evaluation sessions was 60 seconds. If all aircraft are represented by such line we simply check for intersection of these lines to detect potential head-on situation. An additional advantage of this method is that it prevents crossing in front situations as can be seen in Fig. 7b.

3.3.4 Solution Complexity

In the JCS, controllers are able to manually manage perturbations by adding waypoints to the aircraft's trajectory. The travel space always shows the safe places to add a single additional waypoint. To stay close to this way of working, the automation in the JCS always suggests solutions that consist of the addition of waypoints to the 4D trajectory of a flight. This ensures a close resemblance to manually adding a waypoint and

requesting a suggestion from the automation. In the scenarios used for the evaluation sessions for C-SHARE, single waypoint resolutions were always sufficient to solve conflicts. If necessary the complexity of resolutions can be easily increased using the procedure described in Sec. 3.2.

To allow suggestions with a different sector exit time (if resolution of the 4DT within the sector is not possible), the controller must first actively change the sector exit time for the flight (and coordinate with the upstream sector).

3.4 Ranking the Advisories

Solutions not adhering to the criteria of the previous section are not forbidden in the sense that they violate separation constraints. They are rather solutions that are unwanted (because they do not fit the shared mental model) and should only be used if no alternative is available. As the method used to generate resolutions is efficient and quick, a large number of solutions can be created in a very small amount of time. This allows for the introduction of a so-called cost function. A cost function is a function that assigns a single cost value to a solution based on the quality criteria. Especially when multiple criteria are involved it allows for a quality comparison between several solutions. The cost-function used in C-SHARE is calculated as follows.

1. The initial cost for a solution is proportional to its total length (scaled to a value between 1 and 100).
2. For each leg smaller than 25NM, a cost of 50 is added.
3. For each angle smaller than 45 degrees in the trajectory a cost of 50 is added.
4. For each head-on situation a cost 100 is added.
5. Each time the resolution travels on the wrong side of an RA (e.g. CCW when it should be CW or vice versa) a cost of 100 is added.

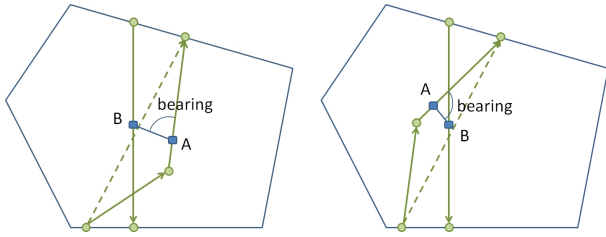


Fig. 8 (a) Flight A diverts to prevent conflict with B, halfway the bearing to B is calculated. (b) A solution in a different homotopy class. The bearing to B is very different than in the left figure.

Sorting the resolutions from small to large cost results in a ranked list of resolutions with decreasing quality.

The JCS has the option to request an alternative solution in case the first advisory is not accepted by the controller. For a controller it would be frustrating if an alternative advisory would be very similar to the first solution (if an advisory does not fit its mental model, a very similar advisory probably also does not). When an alternative solution is suggested, it should therefore be “significantly different” to the first one. A mathematical definition of different paths is given by *homotopy*. Two paths are called homotopic if one can be continuously deformed into the other. As this definition would not work if the JCS is extended to include altitude, we use the following simplified definition: two trajectories are called different if the bearing to the first conflicting flight is sufficiently different. Suppose flight A diverts to prevent a conflict with flight B. Halfway its resolution we check the bearing to flight B from flight A (see Fig. 8a). If two solutions have significantly different bearings to flight B, then we state that they differ (see Fig. 8b). In practice it was observed that any difference larger than 30 degrees suffices to distinguish between resolutions.

Using the above criteria, solutions are called proper alternatives for each other when their difference in bearing is at least 30 degrees. We now again look at the list of ranked solutions and ensure that two subsequent resolutions fulfill the “bearing” criterion by rearranging the order.

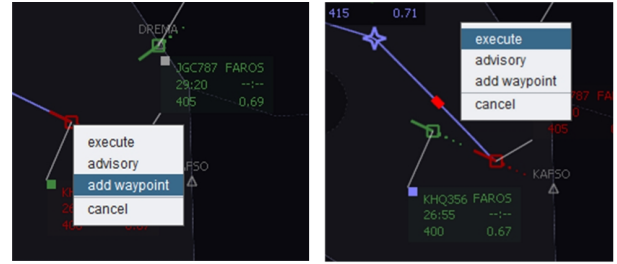


Fig. 9 (a) First pop-up menu to request an advisory. (b) Second pop-up menu to execute an advisory.

3.5 Controller HMI

Parallel to the advisories, the controller HMI (for the interaction with the automation) also went through an iterative design process. In the final version of the JCS a very simple HMI has been adopted, integrating both the travel space and the automation commands. Using a pop-up menu by right clicking a flight enables the controller to command the system. First, an advisory is requested (Fig. 9a). The ATCo can repeat this step if the advised solution is not acceptable. Then by right clicking the advised route, the controller can “execute” the advisory (Fig. 9b). An execute command implies a data-link upload to the aircraft to exchange details of the clearance.

4 Evaluation

The JCS (consisting of travel space, automation and HMI) has been implemented within the C-SHARE project. It has been used to investigate the coordination between the human controller, automated agents and shared representations under varying airspace conditions. Two separate experiments were conducted, a total of twelve test subjects participated in each experiment providing both subjective feedback and digital results (system log files). The focus of the first experiment was to establish the potential merit of the system under varying traffic orderliness and perturbation scales. The aim of experiment 2 was to verify the effectiveness and acceptance of automated suggestions to aid problem solving. In this second experiment participants were free to request and use conflict resolution advisories at

Scenario	Structure	Perturbation
TS_PS	structured	small
TS_PM	structured	medium
TS_PL	structured	large
TU_PS	unstructured	small
TU_PM	unstructured	medium
TU_PL	unstructured	large

Table 1 Definition of the six scenarios

their discretion. By providing this option to the participants, an assessment can be made how and when (under which conditions) automated suggestions support the task of the human operator and uphold shared cognition the most. Focus in this section is on the second experiment.

4.1 Use of Advisories

The independent variables which governed the experiment condition were traffic orderliness (i.e. structured versus unstructured traffic, two levels), and scale of initial perturbation (i.e. number of conflicts and location of restricted area in the sector, three levels). This resulted in six unique scenarios which were the same for both experiments (see Table 1 for details). In each experiment, twelve participants (4 ATCo's, 4 ATM domain experts and 4 Aerospace Engineering students) were asked to execute the six scenarios.

Both experiments were performed with a total of twelve participants, divided into three groups. The first group consisted of four air traffic controllers (area controllers, both certified and in training), the second of four domain experts who are currently working in the ATM domain, the third group consisted of four PhD. students who perform flight-deck and/or ATM related research.

In the remainder of this section focus is on the evaluation results of the *automation* part of the JCS, full details about the other aspects of the JCS can be found in [11].

Fig. 10a shows a bar chart of the average number of accepted advisories per scenario and per subject group in the second experiment. By using a Wilcoxon signed ranks test, the ATCo

group was found to request and accept significantly less advisories than both domain experts ($W(6)=-2.201$, $p < 0.05$) and students ($W(6)=-2.201$, $p < 0.05$). It is clear from the results that when the amount of perturbations increases, the amount of requested advisories increases as well. This is an indication that advisories are mainly used in difficult situations (when workload is expected to be higher). In total, the requested advisory count over all scenarios was 33 (accepted 52%) for the ATCo group, 86 (accepted 69%) for the domain expert group and 120 (accepted 56%) for the student group. Fig. 10b shows a boxplot of the fraction of advisories accepted with respect to the total amount of requested suggestions.

4.2 Questionnaires

A SHAPE ATM Trust Index (SATI) and System Usability Scale (SUS) questionnaire was administered to assess the participants' trust in the suggestions (SATI) and the usability (SUS) of the suggestion function (see Table 2 for details). Both questionnaires were filled in after the first scenario and after the last scenario. The table shows both results.

The answers to the first question ("I used the advisories") differ a lot between the first and second time asked. This was mainly due to the fact that most participants indicated not to have used the advisories in the first scenario.

The SATI statements were rated with a mode of 6 to 7 on all occasions. These questions were rated by all 12 participants and thus indicate relatively high levels of trust on these dimensions of the system. The mode answer for four of the SUS statements was between 5 and 7 (varying from agree somewhat to strongly agree). The mode answer for the question on how cumbersome the advisories were to use was a 2 (disagree) for both times the question was asked. All the SUS answers combined provide an indication of good usability of the JCS advisory system.

4.3 Discussion with Participants

Besides the questionnaires, there was also an open discussion with each participant after the experiment. The following is a result of these

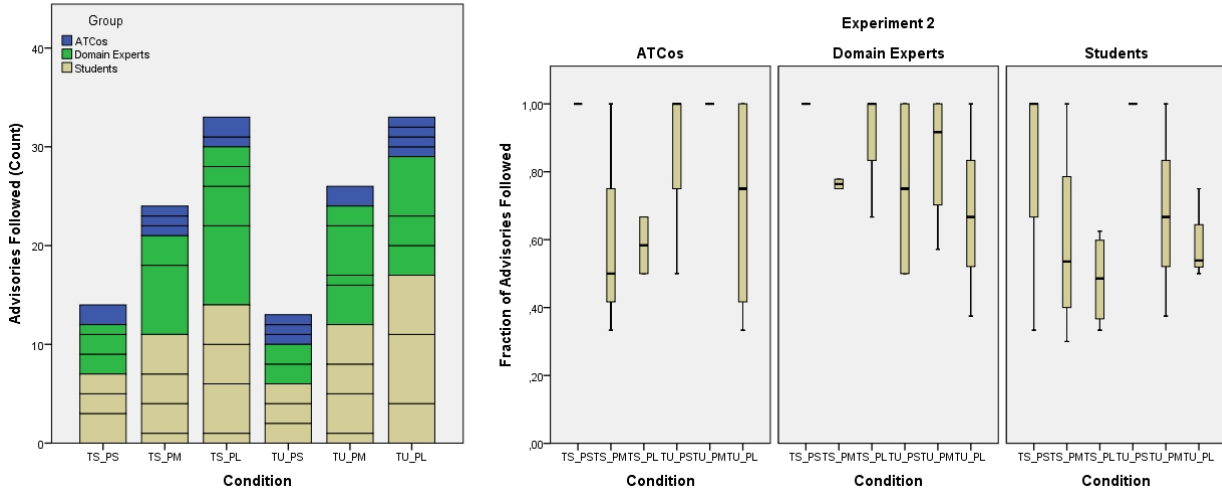


Fig. 10 (a) Bar chart of advisory count per condition, per subject group (b) Box plot of the fraction of followed advisories with regard to the total amount requested

discussions.

The main concern about the advisories is that the solutions they provide are not always seen as the most efficient. In addition to this the participants considered the results to be quite varied, in the sense that sometimes the additional track miles seemed quite excessive and sometimes the solution was deemed as cutting it a bit fine in terms of how close the aircraft was allowed to come to the restricted area. In general, solutions are seen as being reliably safe. This leads to the general consensus that the tool could be useful during periods of high workload, to quickly get a solution that is going to be safe. In cases of lower workload where participants used the advisories, it happened that they agreed with the general solution proposed by the advisory (e.g. right around the restricted area), but then they felt the need to fine tune the waypoint that was placed by the advisory, trying to optimize for the number of additional track miles flown.

The general consensus is that the advisories help reduce workload, as six of the participants explicitly mentioned that. Two participants mentioned that the advisories form a very useful safety net that can be relied upon when the situation gets more difficult. Only one participant did not see a beneficial impact of the advisories on workload, as that person indicated that the travel

Question	Mode
SATI: 1 = never...7 = always	
I used the advisories	1/6
Advisories were useful	6/7
Advisories were reliable	7/7
Advisories worked accurately	7/7
Advisories were understandable	7/6
Advisories worked robustly	6/7
Confident when working w. the advisories	6/7
SUS: 1 = strongly disagree...7 = strongly agree	
Advisory function was easy to use	7/6
Advisory function was well integrated	6/6
Advisories helped to manage workload	7/7
Advisories in accordance w. mental picture	5/6
Advisories were cumbersome to use	2/2

Table 2 SATI/SUS questions and answers after scenario 1 and after scenario 6.

space itself was already very useful in finding appropriate solutions, making the advisories superfluous in his/her opinion.

When asked to what extent the advisories differed from their mental picture of traffic, opinions varied. One participant mentioned that routes proposed by the advisories largely coincided with his/her own thoughts. One participant said that they mostly did not coincide with his/her plans. All others mentioned that proposed advisories varied, where sometimes their own solution would coincide with the one proposed by the advisory whereas in other cases there were large discrepancies between the two. Three of the four ATCos reported that the advisories often did not coincide with their own mental picture of the type of solution that was necessary. The main reason for this was that the solutions were not very efficient and that the solutions required the aircraft to fly an excessive amount of track miles. The conclusion can be drawn that in these cases the reason that solutions do not fit the mental model lies mainly in the fact that they are inefficient, not in the fact that the general idea of the solution is bad.

Two participants did mention that the tool could induce over-reliance of ATCo's on the functionality, saying that if the system would fail (rendering both the travel space and the advisories unavailable) that they think it would be difficult to switch back to a traditional scan and problem solving strategy.

In terms of workload the participating ATCo's have varying views on the relation between workload and the use of the advisories. There was one ATCo who felt that the advisories were useful and reduced workload, whereas two ATCos mentioned that they preferred not to use the advisories during high workload periods. The reasons for not using them under these conditions were that one felt that relying on the advisories reduced the general overview of traffic, while the other mentioned the need to check the solutions proposed, as they were not always deemed reliable. This is supported by the fact that in general ATCo's feel that relying on the advisories will lower their levels of situational awareness.

A final interesting finding is that the accep-

tance of the JCS did not decrease for unstructured traffic with increasing perturbation scale (the conditions of highest complexity) when automated advisories were available. For the same conditions when advisories were not available, results showed that acceptance levels did go down. This shows that the addition of automated advisories was beneficial for the acceptance of the system, especially in more complex scenarios.

5 Conclusions and Future Work

When looking at the results for the use of automated advisories it must be noted that even the most complex experiment scenarios were well solvable by manual control only (i.e. manually adjusting each trajectory using only the travel space visualization). Both during the experiment itself and in the debrief sessions the workload was never reported to be excessive with no free capacity to spare. The use of automated advisories is very likely to increase when higher workload situations arise (high temporal demand) or higher complexity (perturbations harder to resolve manually).

The ATCo group made the least use of automated advisories in general. Following the same reasoning as for the acceptance score, the lesser use of advisories for the ATCo participants can, on the one hand, be attributed to a mismatch in strategic conformance between trajectory-based automation and current tactical ATM operations. On the other hand (as stated previously) the difficulty of scenarios themselves did not require the ATCos to request automated advisories at all. It is foreseen that the advisories will be most beneficial and most used in situations with a high to excessive workload.

The generation of less efficient advisories was one of the main concerns of the participants and should be addressed. Fuel efficiency has not had a large priority when developing the JCS as focus was on the shared mental model, but the experiments have shown that the two are related; inefficient solutions do not fit the mental model of controllers. An easy solution could be to make fuel efficiency an important criterion in the rank-

ing step of the algorithm. In addition a post-processing step could be added to optimize a solution once accepted [14].

Although the experiments were extensive (6 scenarios in 2 hours), gaining confidence and thrust in advices of an automated system takes much more time. If the JCS and its advisories would be used for a longer period, the amount of accepted advisories could increase because the mental models of controller and automation might become further integrated. Small adaptations of the behavior and strategy of the JCS could be helpful in that process.

One of the most significant limitations of the current version of the JCS is the lack of support for altitude in the presentation and resolution of conflicts. The travel space and the advisories generated by the automation are in the 2D plane, not taking into account potential resolutions in altitude. This limitation allowed the project team to concentrate on researching the potential of the travel space and advisories first but the team also realized that support of vertical solutions is necessary for the system to be used in practice. In [11] an extension of the JCS to 3 dimensions (+time) is proposed.

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7 Thanks

The author would like to thank the C-SHARE team for input to various sections of this paper.

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