IMPROVEMENT ON THE ACCEPTANCE OF A CONFLICT RESOLUTION SYSTEM BY AIR TRAFFIC CONTROLLERS

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Abstract

New air traffic management concepts for increasing the capacity of the air space use a longer-term planning than with today's systems realized. The temporally and spatially expanded air space exceeds the cognitive capabilities of humans. Therefore air traffic controllers must be supported technically in terms of conflict detection and resolution. Abstractions of specific conflict resolutions are called conflict resolution strategies. These strategies describe the way of generating solutions, and are independent of the actual conflict situation except for conflict describing parameters.

The air traffic controllers' knowledge about conflict solving was investigated in a literature research. This knowledge was then formulated in the form of hypotheses and examined in a questionnaire-based investigation with air traffic controllers of the German air navigation service provider 'Deutsche Flugsicherung GmbH' (DFS). All hypotheses could be confirmed and besides further knowledge was gained.

The examined hypotheses were then, for further information-technical processing, transformed into a decision tree. This forms the basis for the model of the conflict resolution assistance, which was then transferred with methods of object-oriented software design into a software model and was implemented as software component. The newly created software component was then integrated in the air traffic simulation system of the Technical University Berlin, in order to be validated in a scenario-based real time simulation with air traffic controllers of the German air navigation service provider (DFS).

The evaluation investigation showed an increased acceptance of the conflict resolution assistance system with controllers' knowledge, compared to a system without controllers' knowledge.

Introduction

In recent years new air traffic management concepts have been developed to increase the air space capacity. These new concepts mainly assess the range of the air traffic control and use a longer-term planning than with today's systems realized. Arrangements for capacity increase must also include aircraft based concepts and should not be limited to ground based systems to integrate both sides to a cooperative air traffic management system. [1][2]

Figure 1. Multi-Sector-Planner Working Position

In the context of the DFG (German Research Foundation) research unit 'Man-Machine Interaction in Cooperative Air Traffic Control and Flight Control Systems' a completely evaluated cooperative air traffic management concept was developed, which integrates both cockpit crews and ground control stations. A new medium-term traffic flow planning instance, the so-called *Multi-Sector-Planner* (MSP), is introduced as a core element, shown in figure 1. A goal of the Multi-Sector-Planning is the optimization of the traffic flow beyond existing sector boundaries. The planning area of the MSP consists of several control sectors. With the aim of reducing the traffic situation's complexity and sector load the MSP can change flight paths for these sectors. A planning horizon of 10 minutes to 1 hour has shown to be feasible. By the medium term design of the MSP the planning gap between the longer term management of air traffic flow in Brussels (CFMU) and the short-term tactical planning from sector controllers is closed. The temporally and spatially enlarged air space exceeds the cognitive borders of the MSP controller during the conflict detection and conflict resolution. Therefore the MSP controller must be supported by a medium-term conflict detection and resolution assistance system.

The topic of computer-based assistance systems is already complex, but considering the mathematical generation of conflict resolutions, it is getting even more complex. Reif and Sharir [3] could reduce the 3-satisfiability (3-sat) problem to the problem of motion planning in the presence of moving obstacles in the three-dimensional space, and therefore showing that the problem is NP hard[1] (NP = Non-deterministic Polynomial). That means that for the described problem no algorithm is known, which could solve the problem polynomial time-bounded. For the problem solving this means that in a sufficiently complex situation, e.g. the search for conflict resolutions, the entire solution space cannot be searched and thus it cannot be guaranteed that the solution found is optimal. While with the formulation of a mathematical optimization function it is possible to find a mathematical optimal solution, it becomes more difficult with the inclusion of stakeholders like air traffic controllers and pilots. This fact could maybe explain the large variety of existing conflict resolution systems.

Conflict Resolution Assistance

Kuchar and Yang [5] and Eurocontrol [6] list more than 40 conflict resolution systems, with many different approaches. With over 40 systems existing, however, only few were tested with air traffic controllers and many systems only model partial aspects of the air traffic.

For the introduction of a conflict resolution assistance system the users' acceptance is essential. This can be achieved among other things by the fact that suggested conflict resolutions are plausible and comprehensible for both the air traffic controllers and the cockpit crews. In order to achieve the objective of the assistance system's acceptance, the knowledge of air traffic controllers has to be integrated.

The air traffic controller knowledge can be subdivided into a strategic and a tactical component. The strategic component describes the conflict resolution category (e.g. climb or descent), which should be used for a specific situation. The tactical component concerns the specific generation of a conflict resolution and incorporates operational defaults for the conflict resolution. In figure 2 air traffic controller strategies are shown in the context of air traffic.

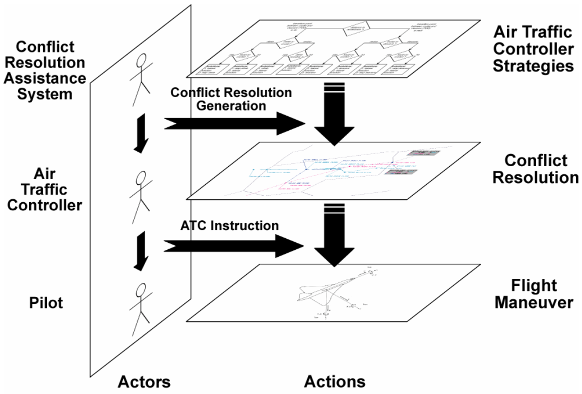

Figure 2. Placement of Air Traffic Controller Strategies in the context of Air Traffic

Starting from the goal of integrating air traffic controller knowledge into a medium-term conflict detection and resolution system, three milestones have been formulated:

- Acquisition of air traffic controller knowledge
- Integration of the controller knowledge in a conflict resolution assistance system
- Evaluation of the conflict resolution assistance system

Acquiring Controllers Knowledge

To achieve the objective of comprehensible and acceptable conflict resolutions suggested by an assistance system, the know-how of air traffic controllers must be integrated.

Conflict solution preferences for en-route traffic were derived from investigations and results of the DFG research unit 'Man-Machine Interaction in Cooperative Air Traffic Control and Flight Control Systems'. These conflict solution preferences depend on four parameters:

- flight phase (climb, cruise, descent)
- distance to destination airport (far, near)
- conflict type (head-on, crossing, catch-up)
- climb possibility (yes, no)

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[1] A decision problem which is computational equal to the class NP (Non-deterministic Polynomial), for which no algorithm is known, who could solve the problem polynomial time-bounded [4].

The investigations to the cube model of Späth [7] and the results of Eurocontrol CORA 2 [8] point to certain patterns as a basis for the solution choice.

Table 1. Solution category distribution for the parameters flight phase and distance to destination airport

Flight phase		climb	cruise		descent
Distance to destination		far	far	near	near
Solution	climb	0%	81.2%	7.1%	3.6%
	stop-climb	75.5%	0%	0%	0%
	descent	0%	5.8%	69.1%	0%
	stop-descent	0%	0%	4.0%	74.1%
	lateral	24.5%	13.0%	19.8%	22.3%

Based on the four mentioned parameters, 36 combinations are possible and 24 combinations are reasonable. For each reasonable combination a scenario was constructed and investigated in a survey with air traffic controllers. The survey with scenario-based questionnaires took place in the ACC Berlin-Tempelhof of the German air navigation service provider (DFS). The participating 24 en-route air traffic controllers worked on traffic scenarios with two conflicting airplanes. The controller could choose their preferred solution among different solution alternatives (speed, vertical and lateral solution) and weight it.

The investigation showed that approximately 97% of all instructions were vertical or lateral flight path modifications. Speed modification solutions or combinations of different solution procedures were hardly selected. This result was also confirmed by air traffic controllers, who use speed modifications more or less only in approach control.

Furthermore airplanes which were near to the destination airport were given a descent solution, while airplanes, which were far from the destination airport, were most frequently given a climb instruction.

An airplane in climb or descent usually was not instructed to change its vertical tendency; this can also be seen in table 1.

With head-on conflicts instructions for lateral modification were used most frequently and vertical solutions were used only rarely, while with the other two kinds of conflict (crossing and catch-up) conditions had turned around.

Additional information could be gained from data analysis, concerning the airplane, which the solution was applied to.

If two airplanes are in cruise, and both differ in the distance to the destination airport, then in approximately 80% the airplane which is nearer to the destination airport will be chosen to change its flight path.

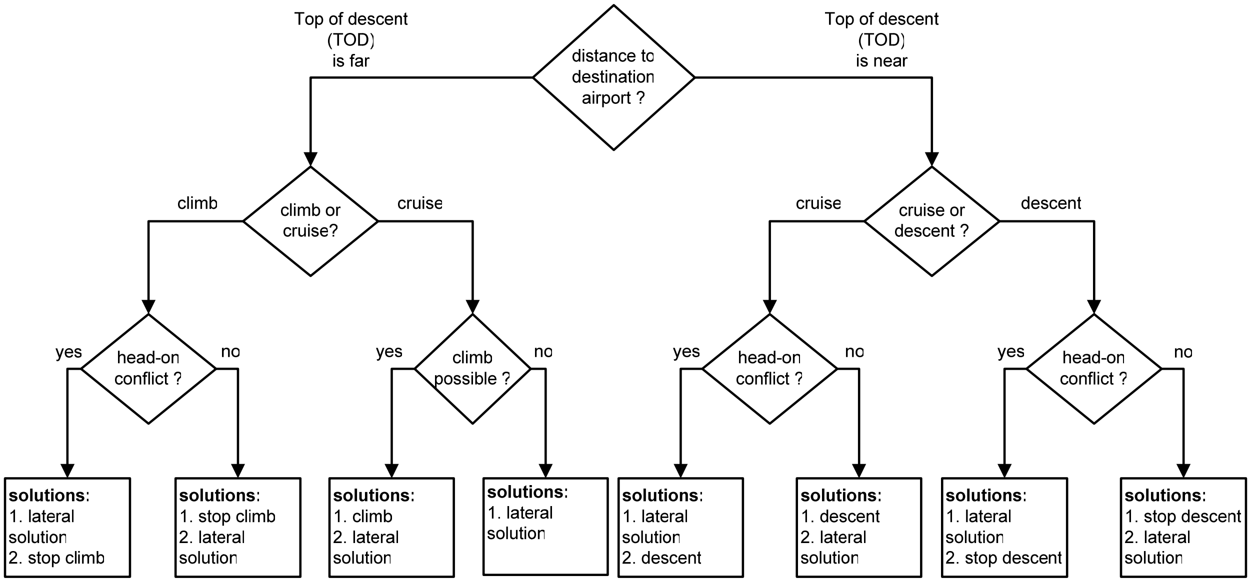

Figure 3. Decision tree for solution choice

If an airplane is in cruise and the other one is in climb or descent, then the airplane which is in climb or descent will be preferably selected and this will be independent from the distance to the destination airport and the climb possibility.

For further information-technical processing the conflict resolution generation was treated as a multi-class classification problem with the solution set S={climb, descent, stop-climb, stop-descent, lateral}. This means, that each conflict situation will be classified to an element of the solution set S and for this element a conflict resolution will be generated by heuristic search methods.

To be able to perform the classification task, the gained knowledge must be represented suitably. A knowledge representation form for multi-dimensional discrete variables is a decision tree [9]. A decision tree stores the knowledge in a tree-similar structure. It starts at the top with the root element and ends after various test conditions with a leaf element. The leaf element contains an element from the solution set. The knowledge is therefore stored in the path, which directs to the leaf element.

Deviating from the standard decision tree, the leaf element contains a solution list with prioritised disjoint solution elements from the set S, as shown in figure 3. Following test conditions with their attributes are used:

- flight phase (climb, cruise, descent)
- distance to destination airport (far, near)
- conflict type (head-on, no head-on)
- climb possibility (yes, no)

Additionally a second decision tree exists, which models the airplane choice. The output of this decision tree is the selection of the airplane to be changed. This can be the first airplane, the second airplane or both airplanes.

Knowledge Integration into the Conflict Resolution Assistance System COCOS

The controllers' knowledge, which is represented as controllers' strategies in the decision trees for solution and airplane choice is embedded in a superordinated conflict detection and resolution system. The model for the used system is shown in figure 4 as activity diagram in UML (Unified Modeling Language) notation. The activity diagram shows the flow of control from activity to activity. An activity is shown as a rectangle with rounded corners and describes sequential and concurrent computation [10].

The model starts with temporal and spatial reduction of solution space to limit the pairwise conflict detection. For each detected conflict, the conflict situation must be classified with the decision trees for airplane choice and solution choice.

In some cases a definite airplane assignment could not be found in the investigation. In such situations, for both conflict partners solutions are produced. Following the decision tree of solution choice, a single merged solution list will be obtained. For each item in the solution list a specific solution will be generated with heuristic search methods. This solution will be tested for a new induced conflict in a fast-time simulation. The generated solution will be then modified until an abort criterion or a given time-threshold is reached.

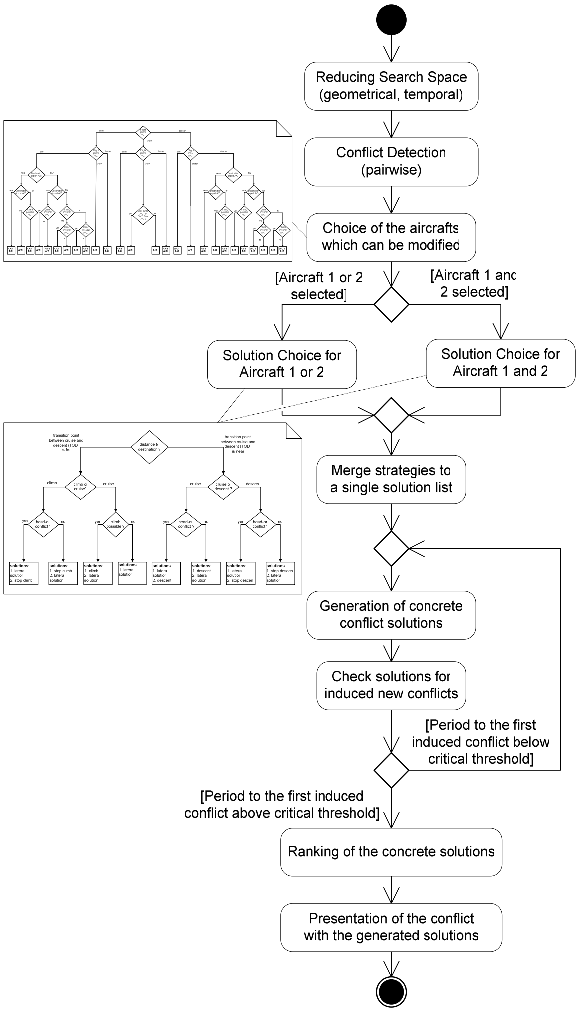

Figure 4. Activity diagram for the conflict detection and resolution model

In a further step, the specific conflict resolutions will be sorted within their solution category (vertical, lateral), so the controller preferences will not be affected. As a sorting criterion for lateral solutions is the induced delay, while for vertical solutions the minimal deviation from the planned flight path is used. As the last activity the generated solutions are presented to the air traffic controller.

Conflict Resolution Software Component

For the evaluation of the described conflict resolution model, a software component is necessary, which can be integrated into the ATC simulation system of the Technical University Berlin. The new developed software component COCOS (Controllers strategies integrated into a Conflict resolution System) is to be examined in a real time simulation study with an existing experimental controller working position, the *Multi-Sector-Planner* (MSP). In order to be able to compare the newly developed software component COCOS with the prior system LOTEC in an evaluation investigation, it is necessary to have an interface compatibility for both systems with the MSP. This can be achieved by decoupling the MSP from the conflict resolution assistance system.

The software component COCOS was implemented in the programming language C++ to guarantee interface compatibility with its predecessor system LOTEC. The component COCOS is implemented as an independent software library, which is supported by a data recording component (Log4Cplus). The component model of COCOS is shown in figure 5 in UML 2.0 notation. The component diagram shows the relationship between components, their external interfaces and component artefacts like 'library' or 'executable'. A provided interface is shown as circle attached to the component, while a required interface is shown as semicircle attached to the component [10]. The component essentially consists of the control instance 'Cocos' and the following three subsystems:

- **Trajectory Prediction**: Transformation of the coarse-grained flight plan data into planned fine-grained four-dimensional flight profile data. Results of this activity are trajectory data.
- **Conflict Detection**: Pairwise detection of dropping below the permissible minimum vertical and lateral distances between airplanes on the base of the trajectory data. Results of this activity are the detected conflicts.
- **Conflict Resolution**: Modification of the trajectory, with consideration of controller strategies, of one or more airplanes, so that the minimum distances between the airplanes are met. Results of this activity are the conflict resolution suggestions.

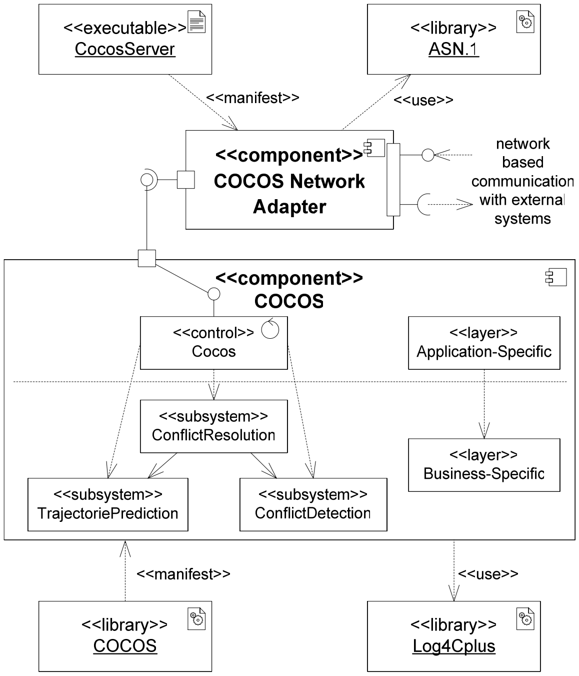

Figure 5. Component diagram for the realized software component COCOS

The control instance 'Cocos' makes an external interface available. It controls and coordinates the three subsystems mentioned above. First, trajectory data are computed from flight plan data. Based on the trajectory data conflicts are detected and in addition conflict resolution suggestions are generated.

During the generation of conflict resolutions individual trajectories are changed to solve conflicts. Therefore a trajectory recalculation with the newly computed trajectory data is necessary in order to examine, whether the conflict was eliminated or further conflicts were induced by the solution.

During the generation of conflict resolutions it is important that the flight performance boundaries are not exceeded. Therefore flight performance computations based on Eurocontrol BADA data [11] are performed, to ensure that a solution suggestion does not have to be rejected by the pilot, only because the airplane cannot perform it. Such a rejection by the pilot would also reduce the acceptance of the conflict resolution assistance system by the air traffic controller.

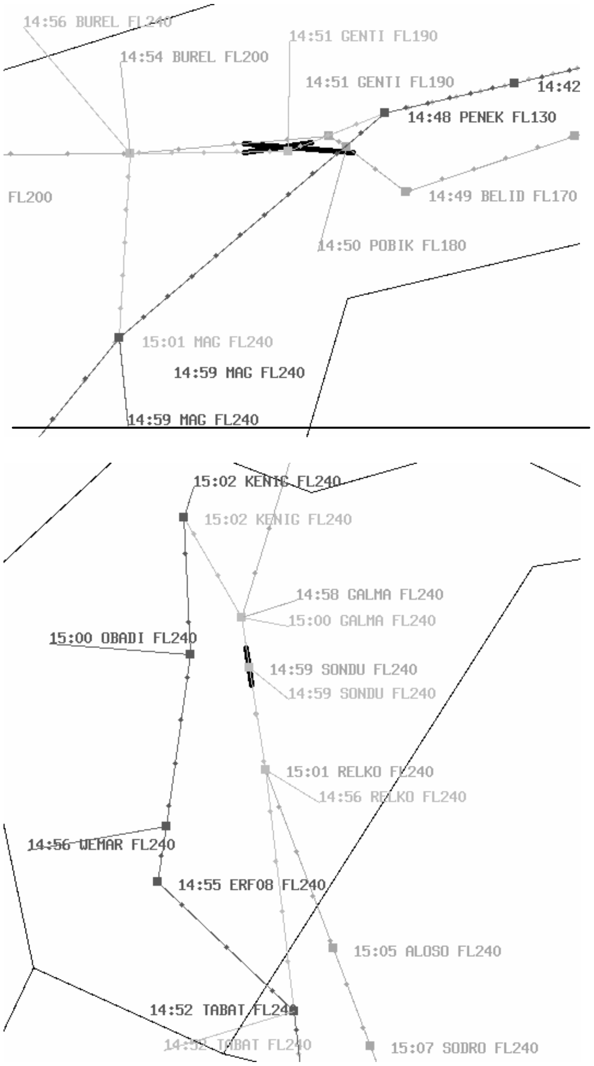

Figure 6. Examples for lateral conflict solution suggestions. The planned routes of the conflict partners are light grey, conflict resolutions are dark grey and the conflict area is represented in black. Waypoints of the route are visualized by squares, with the indication of the ETO (Estimated Time Over), the waypoint name and the altitude.

Figure 6 shows two examples of lateral conflict resolution suggestions generated with the software component COCOS and visualized with the Multi-Sector-Planner. The planned trajectory for each conflict partner is shown in light grey, conflict resolution suggestion in dark grey and the conflict area is represented in black. Waypoints of the route are visualized by squares, with the indication of the *ETO* (Estimated Time Over), the waypoint name and the altitude. The solution at the top of figure 6 was produced with a simple backtracking search algorithm, while the solution at the bottom was generated with a complex graph search[2] with constraints. A detailed description of architecture and the algorithms of the software component can be found in [12].

Evaluation of the Controller Assistance System COCOS

The integration of controller strategies aims for an increased compatibility between human decisions and suggestions of the solution support system.

For the examination of the conflict solution assistance system's influence on the participating controllers, they supervised the MSP area under three conditions in the context of different air traffic scenarios:

- Control condition with conflict detection and without conflict solution suggestions
- Test condition with conflict detection and conflict solution suggestions without controller strategies (LOTEC)
- Test condition with conflict detection and conflict solution suggestions with integrated controller strategies (COCOS)

For the evaluation of COCOS three comparable scenarios were developed, which differ according to substantial air traffic parameters. The scenarios are based on air traffic data provided by the DFS, which was systematically varied for examination of controller strategies. The parameters 'distance to destination airport', 'flight phase', 'conflict type' and 'climb possibility' were varied. In the control condition the air traffic controller had to supervise the air space of the MSP area without the conflict resolution system. In the following two test conditions the controllers were supported by a conflict resolution system. In all three conditions detected conflicts were shown to the controllers textually on a support screen and visually on the radar screen. The controllers were instructed to solve as many conflicts as possible in flight plan negotiations. The sample consisted of 27 en-route controller of the ACC Berlin-Tempelhof of the German Air Navigation Service provider (DFS). During the investigation eye tracking, behaviour measurement and questionnaires were used.

A comparison of processing times showed that the test participants needed statistically significant

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[2] modified A*-algorithm with geometric constraints and checking for absence of new conflicts, q.v. [9][12]

longer for conflict solving with LOTEC (103.95 s) compared to COCOS (78.23 s).

By comparing the selected conflict solution suggestions in both test conditions with the control condition, it is possible to get a measure for accordance between air traffic controller preferences and the conflict solution suggestions of the assistance system. The accordance between air traffic controller und LOTEC is 44% and between controller and COCOS 66%.

Regarding all conditions, the agreement on the first conflict solution suggestion is 51% and on the first and second conflict solution suggestion is 75%.

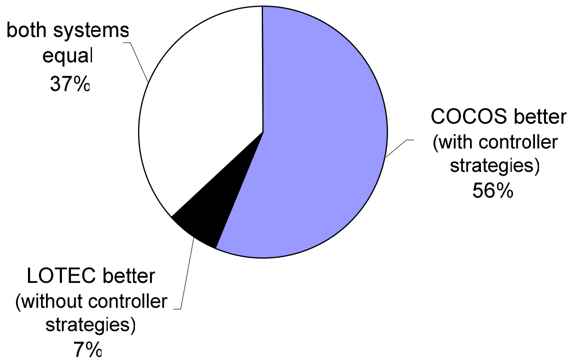

Figure 7. Acceptance of the solution systems

In the interview all test participants were asked for a comparing assessment of the two solution systems. Thus, 56% of the controllers preferred the solution suggestions of COCOS, 7% preferred the solution suggestions from LOTEC and 37% could not differentiate between the two systems, as is shown in figure 7.

Results

Visual Statistical Data Analysis

A visualization method for multivariate categorical data is the *Multiple Correspondence Analysis* (MCA). This method can be viewed as a *Principal Component Analysis* (PCA) of the indicator matrix build by the factors and levels of categorical data. The principal component analysis is a linear transformation, which maximize the variance of a linear combination of variables. While the first principal component is the linear combination with maximal variance, the second principal component is the linear combination with maximal variance orthogonal to the first principal component. In figure 8 the first two principal components of the indicator matrix are shown in a biplot, which visualizes the observations and variables in a 2-dimensional map. This allows a deeper analysis of the relationship between the observations and the variables. Points in proximity to each other in the biplot indicate an association. [13][14][15]

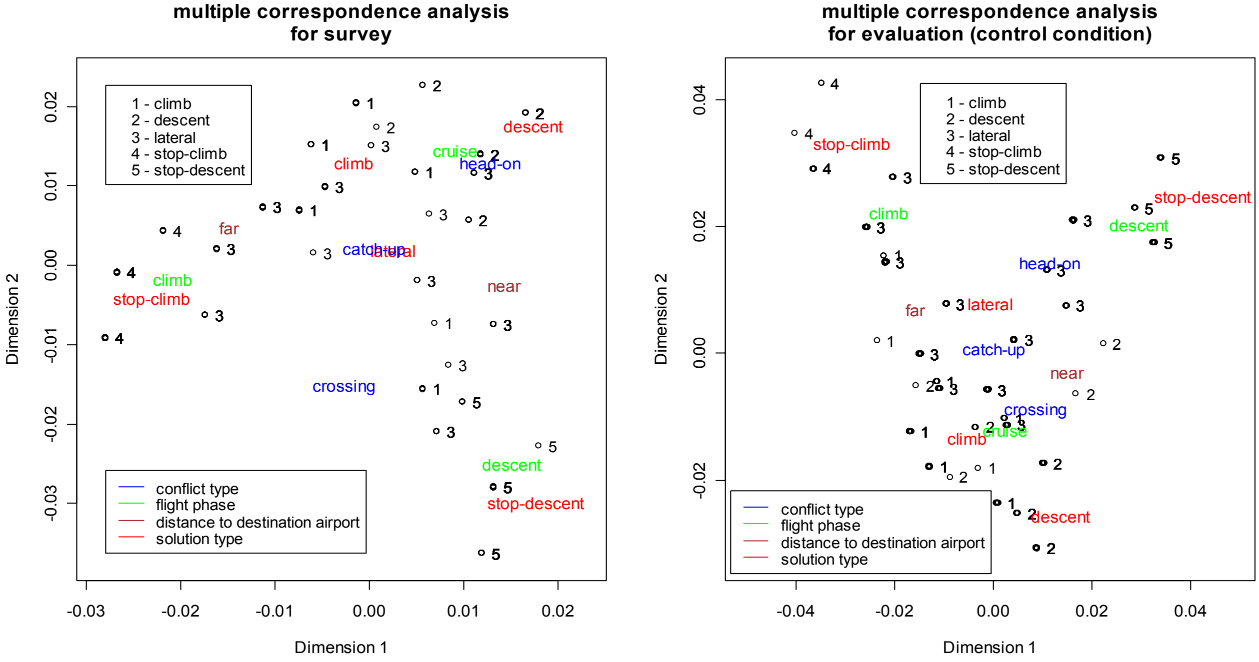

Figure 8. Multiple correspondence analysis for survey and evaluation (control condition)

In figure 8, elements from the solution set are numbered from 1 to 5 and labelled next to the observations, which are indicated by a small circle. The mean of the observations associated to a solution element is plotted as solution element name.

It can be read off from figure 8 that a ‘stop-climb’ solution is predominantly instructed in the flight phase ‘climb’ and a ‘stop-descent’ solution is predominantly instructed in the flight phase ‘descent’. ‘Climb’ and ‘descent’ solutions are predominantly instructed in the flight phase ‘cruise’. It can also be seen, that the flight phase ‘climb’ is closer to the value ‘far’ and the flight phase ‘descent’ is closer to the value ‘near’ concerning the variable ‘distance to destination airport’. But it seems to give only a weak relationship between the variable ‘distance to destination airport’ and the solution categories ‘climb’ and ‘descent’. Furthermore the solution category ‘lateral’ can poorly be assigned to any of the variables.

Even if the Multiple Correspondence Analysis for both investigations in figure 8 looks different, the represented connections are mostly similar. It seems there is as a stronger relationship between the variable ‘distance to destination airport’ and the solution categories ‘climb’ and ‘descent’ in the survey investigation compared to the evaluation investigation, but this can be due to the scenario setup.

Error estimation of the decision tree

While the visual statistical data analysis showed qualitative accordance between the air traffic controller and the assistance system, a quantitative performance measurement of the decision tree would be interesting. The statistical learning theory provides a simple way of measuring the error rate of a discriminating function. With the conflict describing input vector ***x***, the corresponding conflict solution set *y* and a transformation function $f(\boldsymbol{x},\boldsymbol{\alpha})$ with the parameter vector $\boldsymbol{\alpha}$, a loss function can be defined, the so called 0/1 loss function [16]:

$$L(y,f(\underline{x},\underline{\alpha}))=\begin{cases}0 \quad , \quad y\in f(\underline{x},\underline{\alpha})\\ 1 \quad , \quad y\notin f(\underline{x},\underline{\alpha})\end{cases} \tag{1}$$

The loss function measures the loss or discrepancy between the response variable or response set *y* and the output of the transformation function $f(\boldsymbol{x},\boldsymbol{\alpha})$. With this function an error rate can be estimated by integrating over the sample, or in case of a discrete input variable by summarizing. For a sample of size ℓ, the error rate can be estimated by the error function:

$$\mathrm{Err}(\underline{\alpha})=\frac{1}{\ell}\sum_{i=1}^{\ell}L(y,f(\underline{x},\underline{\alpha})) \tag{2}$$

With this error function the error rates can be estimated for the first solution of the decision tree, as shown in table 2.

In the case of conflict solution classification, an error rate of zero can not be achieved, because different air traffic controllers assign different solutions in the same conflict situation. To estimate the lowest possible error rate for the given sample, an optimal decision function must be defined. The Bayes classifier can be used as decision function, who is known to predict optimal [9].

The Bayes classifier makes predictions based on the most probable hypothesis, the so called maximum a posteriori (MAP) hypothesis [9]. If input and output are known, the MAP hypothesis for a conflict situation can be easily found. An optimal Bayes classifier would achieve the error rates shown in table 2 for the given sample.

Because the decision tree responds to a conflict situation with two solutions in most cases, the error rates for the decision tree were reduced, as shown in table 2. The same applies for a Bayes classifier, who predicts the most probable vertical and lateral solution.

Table 2. Error rates for both investigations and different classifier

	$\mathrm{Err}_{\mathrm{Survey}}$	$\mathrm{Err}_{\mathrm{Evaluation\ (Control\ Condition)}}$	$\mathrm{Err}_{\mathrm{Overall}}$
Decision tree – first solution	0.268	0.425	0.349
Bayes classifier – most probable solution	0.138	0.249	0.194
Decision tree – all solutions	0.173	0.197	0.188
Bayes classifier – most probable vertical and lateral solution	0.032	0.072	0.052

Table 2 shows a greater difference between the survey and the control condition of the evaluation. This can be caused by the different scenario setups.

The 24 survey scenarios contained only two aircrafts with well designed flight plans, while the four evaluation scenarios contained up to about 80 aircrafts, based on recorded flight plans. As the recorded flight plans missed some information, they had to be manually completed, which caused errors.

The Bayesian classifier is optimal fitted to the sample data, which would cause worse performance for new unseen data but would give a good estimate for the lowest achievable error rates. The error rates in table 2 show that a better fitted decision tree could enhance the performance. While enhancing the performance of the discriminating function, the overfitting of the Bayes classifier must be avoided.

Conflict Resolution Prediction as Minimisation Problem

The error estimation chapter showed a mean performance for a classifier, which tries to predict the most probable solution. If the classifier would instead predict the most probable solutions for a conflict situation, performance could be quite pushed forward, by a moderate number of additional solutions. This would also reduce the average number of solutions compared to the decision tree and the air traffic controller would rather found his preferred solution.

The described problem can be formulated as minimization problem, where the most probable solutions for a conflict situation are searched, with a joint probability $\Sigma_j P(y_j|\mathbf{x})$ greater equal a given threshold θ,

$$\hat{j} = \underset{j \in \{x \mid x \subseteq \{1,\ldots,5\} \wedge x \neq \emptyset\}}{\operatorname{argmin}} \left(|j|, 1 - \sum_j P\left(y_j \mid \underline{x}\right) \right) \qquad (3)$$

$$\text{subject to} \quad \left(\sum_j P\left(y_j \mid \underline{x}\right) \right) \geq \theta,\ \theta \in (0,1]$$

resulting in the searched solution set $y_{\hat{j}}$.

The unknown probability $P(y|\mathbf{x})$ can be estimated by the probability $p(y|\mathbf{x},\boldsymbol{\alpha})$ of the discriminating function $f(\mathbf{x},\boldsymbol{\alpha})$, which can be inferred inductively or deductively with statistical or machine learning methods.

Future Work

With the minimisation problem formulated above it is possible to learn the air traffic controller behaviour by induction or deduction. A suitable learning method should be searched and integrated into the conflict resolution model to enhance the agreement between air traffic controllers and the assistance system.

Conclusions

The results confirm that the selected approach is suitable to increase the compatibility and reliability of the solution system by integration of controller knowledge. A deeper analysis of the results points out possibilities to improve the model.

In order to better adapt the model to the controllers' behaviour, further conflict relevant parameters must be examined and the model should be extended to be more flexible about the most probable resolutions.

Interviews suggest interesting additions, which can lead to an extension of the airplane choice model. Sometimes controllers criticized that they could not find solutions for their preferred airplane.

The evaluations showed the importance of the parameter 'distance to destination airport' for the solution choice. Therefore it is evidently important to examine this parameter more detailed in further iterations, to improve the acceptance and the transferability to other conflict situations.

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Keywords

Air Traffic Control, Conflict Resolution, Air Traffic Controllers Strategies, Assistance System, Conflict Detection and Resolution Assistant System, Medium-Term Conflict Detection and Resolution

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