Final Report

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Abstract

The final report of the SUPEROPT project provides a publishable summary of the results. In addition it lists all deliverables, dissemination activities, eligible costs, deviations, bills and lessons learned.

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Publishable Summary

Goals

Numerical trajectory optimization is well-studied, and with SESAR's focus on trajectory-based operations, it is logical to investigate what role trajectory optimizers might play in future ATM. However, existing trajectory optimizers tend to ignore any human role and offer interfaces only in awkward mathematical terms, for developer tuning. SUPEROPT (Supervision of Route Optimizers) has looked at translations between the mathematical forms needed for optimizers and more usable human forms of behaviour and information, to see if optimizers could be exploited at lower levels of information.

Enabling Supervisor Input

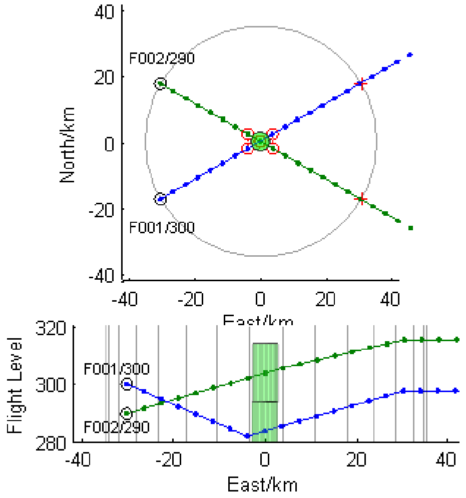
SUPEROPT has developed formulations for expressing some typical human conflict resolution strategies in a trajectory optimizer. These include:

- resolve conflict vertically only
- resolve conflict with aircraft A passing over aircraft B
- resolve conflict horizontally only
- resolve conflict with aircraft A passing ahead of aircraft B
- ensure aircraft A leaves area ahead of aircraft B
- resolve conflict by speed change only

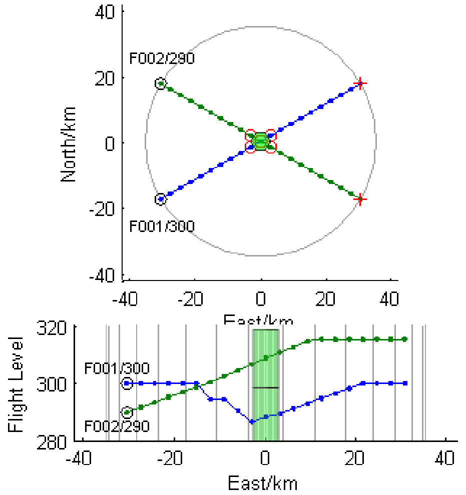
The SUPEROPT concept is that the controller selects strategies to be applied to various aircraft (or pairs of aircraft). These are then translated into constraints added to a multi-aircraft trajectory optimizer. The applied constraints are added on top of all-pairs of separation constraints, meaning that there are no knock-on effects, and that conflicts for which no strategy is specified will be resolved using whichever method is preferable according to the optimizer's objective.

Two types of trajectory optimizer have been studied. One employs Mixed-Integer Linear Programming (MILP) and a commercial global solver code. Aircraft dynamic capabilities are modelled using BADA data. The second optimizer uses a nonlinear solver and offers more flexibility of modelling, such as the potential to include aircraft noise impact models, but at the expense of only local optimality of solutions. The toolbox of strategies identified above has been implemented for both optimizers. Figure 1 and Figure 2 show examples from the MILP optimizer of horizontal and vertical resolution strategies.

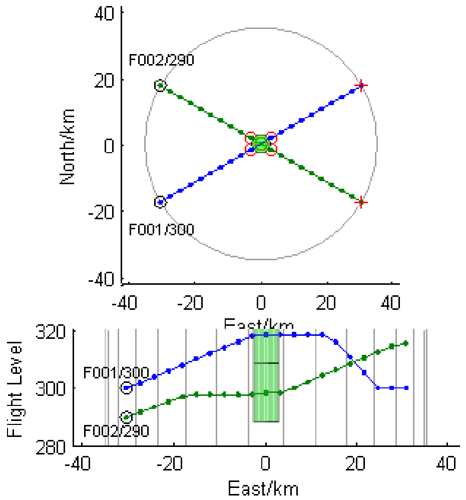
All of these tools have been integrated into a demonstration platform using the MILP optimizer to work with a Multi-Sector Area over Wales and north-west England. Public aircraft track data has been recorded and shifted in time to provide a dense traffic situation with conflicts. Figure 3 shows screenshots of this demonstrator, including the Toolbox for applying the different strategies. *Note that SUPEROPT has focussed on the implementation of the optimizer and constraints, not the human factors associated with their use, so these demonstrators are for research use only.*



Unconstrained

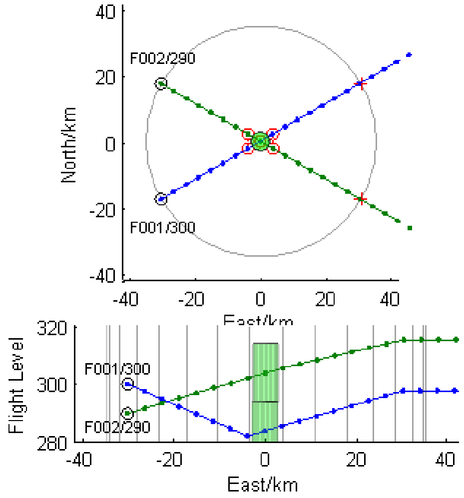


Resolve vertically



F001 over F002

Figure 1: Vertical resolution results



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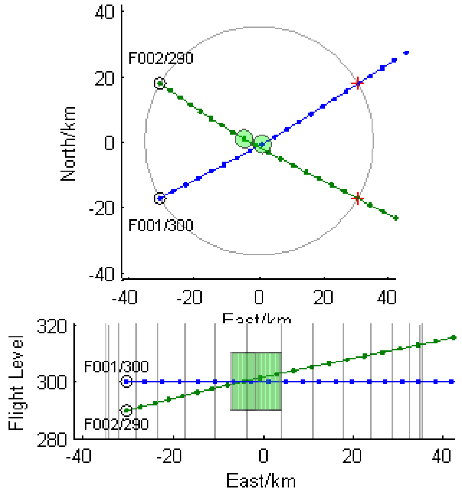
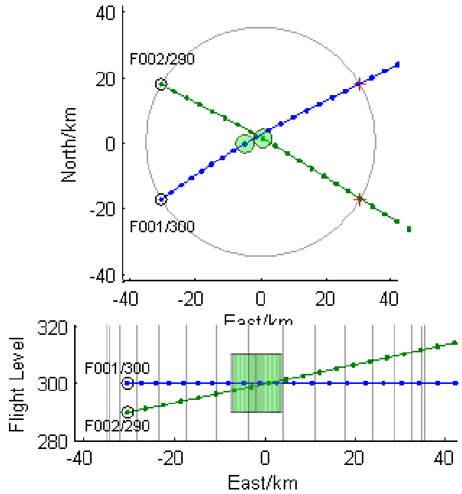


Resolve horizontally with F001 ahead of F002



Resolve horizontally with F001 behind F002

Figure 2: Temporal resolution results

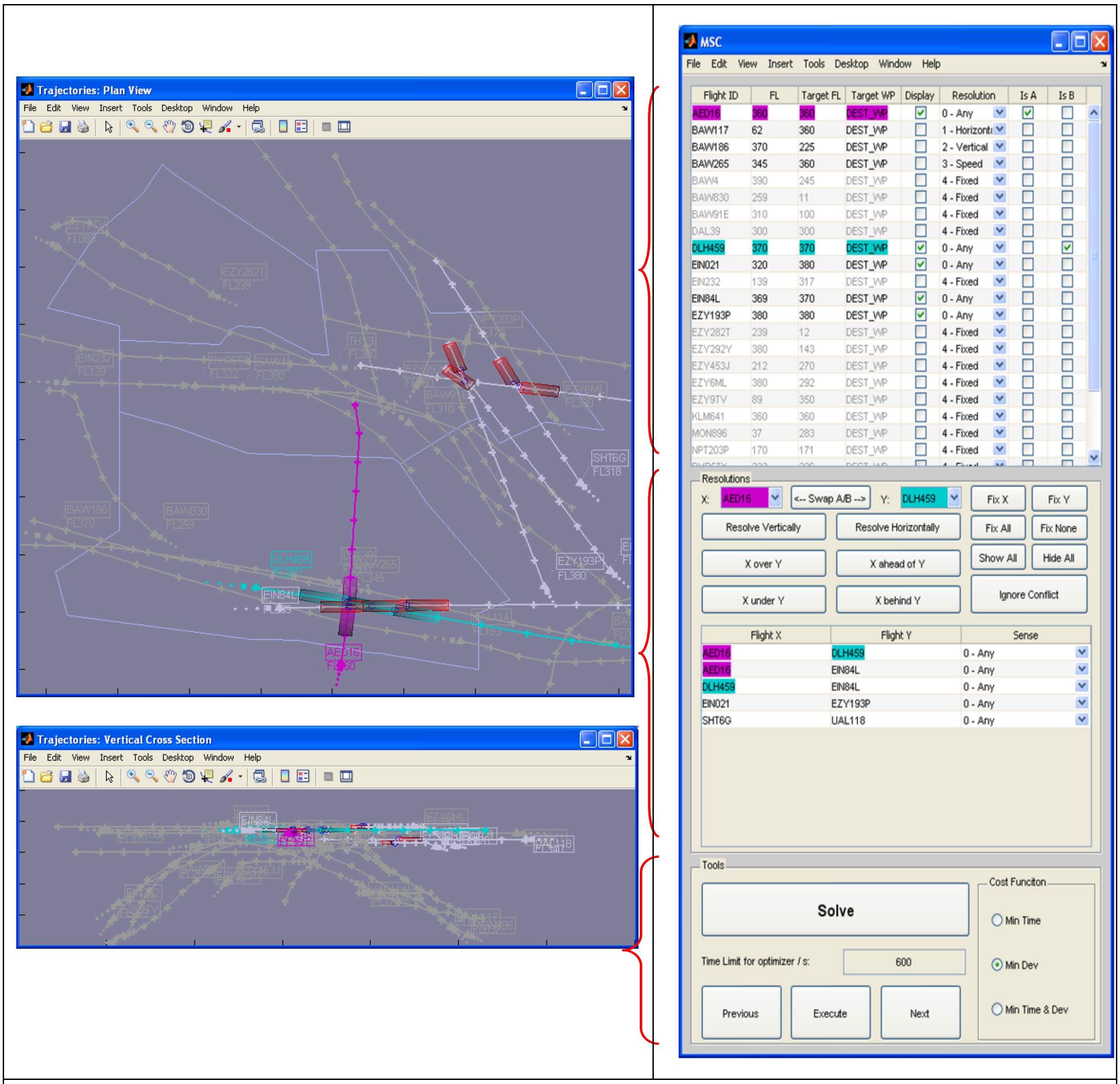


Figure 3: MSC Demonstrator

Informing the Supervisor

The complement to enabling input is to provide sufficient analysis of the optimized solution, such that the supervisor can understand the rationale on the resolved trajectories ("why?") and make an informed decision on its use. SUPEROPT has developed several approaches to this aspect of the problem.

The first and most simple tool is the identification of the active constraints. Markers are added to the displays in Figure 3 to show which aircraft pairs are at their separation limits and when.

An additional tool is a cost history, which shows how the quality of the optimized solution changes as constraints are altered. The supervisor can proceed through a series of strategies, adding or removing constraints and re-solving each time, observing how the cost changes. Then "back" and "forward" navigation buttons are provided to enable the supervisor to switch between options and select the most preferred.

An additional development for information is a post-processing technique to extract meaningful alternatives from a sequence of trial solutions. For diversity, this was investigated using a case study on flow scheduling subject to runway capacity constraints in an imaginary airspace. Delays were assigned to five hundred flights using a stochastic optimizer. Figure 4 shows the best six solutions from one run. Long red bars mark long delays and short green bars mark short delays. Note that the six are all highly similar (although distinct, in small ways) and therefore do not provide a meaningful range of options for a supervisor to choose between. Figure 5 shows six alternatives extracted from the same run using the “Alternatives” approach, solving a fast multi-objective search to balance performance against novelty, and producing six much more distinct solutions to be considered.

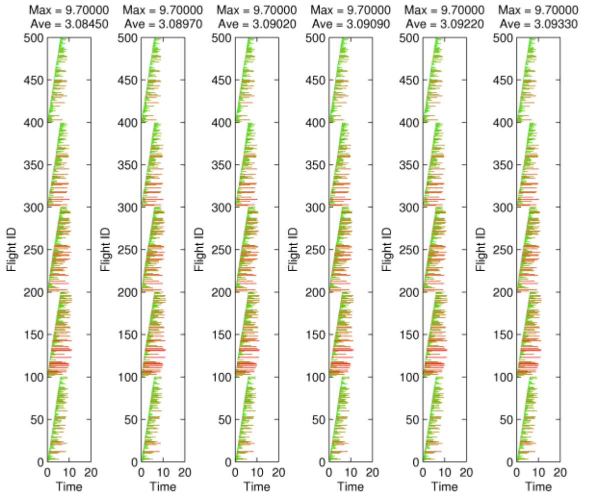


Figure 4: Best Six Solutions

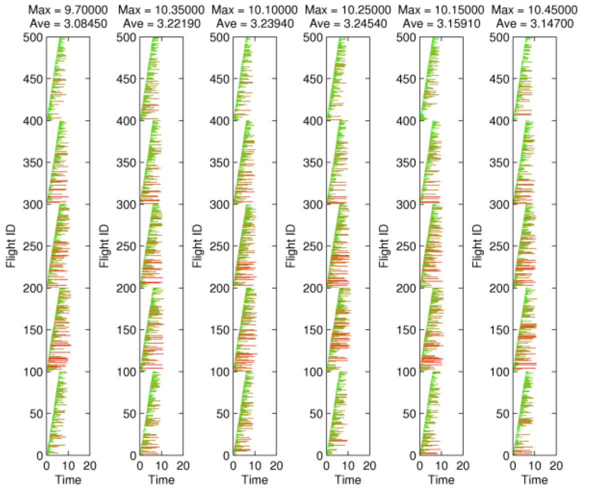


Figure 5: Six Alternatives identified by the "Alternatives" Algorithm

Conclusions

SUPEROPT has found mathematical translations between human ATM strategies and mathematical constraints on trajectory optimizers. Demonstrations have shown that the methods work as expected and hence offer the potential for a supervisor to have meaningful control over an optimizer. Analyses have been added to help the supervisor interpret the results. Overall, the project has shown ways to employ optimizers at low levels of automation. However, trajectory optimizers can pursue more complex decision making than human controllers (e.g. cooperative resolution of conflicts by changes to multiple trajectories) and significant human factors challenges remain open.

1 Introduction

1.1 Purpose of the document

The purpose of this document is to:

- Summarise the technical results and conclusions of the project (Publishable Summary);
- Provide a complete overview of all deliverables;
- Provide a complete overview of all dissemination activities (past and in progress). Where appropriate, provide feedback from presentations. Describe exploitation plans.
- Provide a complete overview of the billing status, eligible costs, planned and actual effort (incl. an explanation of the discrepancies).
- Analyse the lessons learnt at project level.

1.2 Intended readership

ATM practitioners and developers interested in the use of trajectory optimization for automation can learn the major findings of the SUPEROPT project from this document. In particular, SUPEROPT has found various translations between human decisions in the context of ATM and the mathematical language of numerical trajectory optimization. This enables optimization to be exploited at relatively low levels of automation.

1.3 Inputs from other projects

The Challenge Scenarios were developed around roles outlined in the PHARE **[6]** and ADAHR **[7]** EUROCONTROL projects. Understanding of the Network Manager challenge scenario was inherited from the ONBOARD SESAR WP-E project.

1.4 Glossary of terms

N/A

2 Technical Project Deliverables

Number	Title	Short Description	Approval status
D1	Project Definition and Literature Review	A pair of challenge scenarios is described in terms of the proposed interactions between the supervisor and the optimization. Proposed optimizers are discussed. A 3 D performance model is incorporated into a MILP collision avoidance algorithm based on the EUROCONTROL Base of Aircraft Data (BADA). Initial results for constraining the sense of conflict resolution are presented using four separate formulations: one for 2 D and three for 3 D conflict avoidance.	Approved
D2A	Draft version of “Enabling Supervisor Input”	This document was an initial version of D2, reporting on mid-project progress on supervisor input methods. See summary of D2 below for details. All work in D2A was later reported in full in D2, which supersedes D2A.	Approved
D3A	Draft version of “Informing the Supervisor”	This document was an initial version of D3, reporting on mid-project progress on supervisor information methods. See summary of D3 below for details. All work in D3A was later reported in full in D3, which supersedes D3A.	Approved
D2	Enabling Supervisor Input	This document reports the methods developed by the SUPEROPT project for supervisor interaction with optimizers. Two mathematical forms for an optimizer to support a Multi-Sector Controller are presented and compared, including various constraint forms to enable flexible but intuitive supervisor input. Enabling supervisor input to the optimization ensures the supervisor retains control of the high level decision making while leaving the optimizer to perform the low-level detailed trajectory design.	Submitted
D3	Informing the Supervisor	This document reports the methods developed by the SUPEROPT project to inform a supervisor about the decisions made by optimizers. An approach for using the output of the optimizer to enhance the Supervisor’s understanding is presented along with a method to explore complex multi-objective solution spaces. Stochastic optimizations of the Network Manager role are developed and analysis of the method iterations is shown to give useful insight into the solution process as well as providing alternative solutions to a given problem instance.	Submitted
D4	Supervision of Trajectory Optimizers	The document presents an evaluation of the MSC planner tool and associated algorithms developed by the SUPEROPT project. A brief guide to the tool is given along with some sample results. A discussion of the limitation of the results in the context of an operationally useful tool is given and illustrations of how the algorithms can be modified to address them are shown.	Submitted

Table 1 List of Project Deliverables

3 Dissemination Activities

3.1 Presentations/publications at ATM conferences/journals

Constraining the Sense of Conflict Resolution: Supervision of Route Optimization [8]
First SESAR Innovation Days, 2011

This paper develops a form of constraints for constraining the *sense* of a conflict resolution within a trajectory optimization. The goal is to enable an intuitive but flexible tool for human supervision, enabling the human to request a particular sense of resolution without conservatively constraining the optimizer. The new constraints are based on the total change in angle of the line joining the two aircraft, which can be uniquely related to one aircraft passing ahead of or behind the other. The method has been implemented with Mixed-Integer Linear Programming as the optimizer and demonstrated in simple scenarios of air traffic control within a sector.

Examples of Supervisory Interaction with Route Optimizers [9]
Second SESAR Innovation Days, 2012

This paper develops a 3-D aircraft performance model and then concentrates on giving a supervisor the ability to select their desired “sense” of conflict resolution between multiple aircraft; time is included in the model to allow one aircraft to pass “ahead” or “behind” another. A nonlinear model with equivalent sense constraints is also developed to facilitate the inclusion of fuel use or potentially noise and emissions in future developments. The linear model is applied to a large scale problem and a tool is presented to facilitate exploration of the solution space created by the available sense constraints and additionally by different cost/objective functions before “committing” to a specific solution.

4-D Trajectory Optimizers for Conflict Avoidance Using Speed Advisories [10]
Tenth USA/Europe Seminar on ATM R&D (to appear), 2013

This paper extends 4-D trajectory optimizers to resolve conflicts through “speed advisories”, separating high-level decision making from the detailed trajectory optimization. Details of Mixed Integer Linear Programming (MILP) and collocation optimizers are briefly reviewed before the additional constraints are developed to force resolution only through speed changes. Results for a multi-sector area over Wales and North-West England illustrate how the method can be used. A brief evaluation of the computational complexity of the method is shown.

3.2 Presentations/publications at other conferences/journals

Collocation Methods for Multi-Vehicle Trajectory Optimization [11]
European Control Conference (to appear), 2013

Direct collocation offers an efficient way of transcribing optimal control problems to form nonlinear optimizations. Collocation is particularly attractive for variable time problems as the finishing time can be made a decision variable. However, this causes problems in coupled multi-vehicle problems, for example, where different vehicles may have different finishing times. This paper proposes a way of capturing coupling constraints - in particular, collision avoidance - between vehicles without requiring a common time of arrival. The approach exploits a recently-developed dualization approach for avoidance constraints, extended to act in time as well as spatial dimensions.

Inter-Sample Avoidance in Trajectory Optimizers using Mixed-Integer Linear Programming [12]
AIAA Guidance Navigation and Control Conference (to appear), 2013

This paper proposes an extension to trajectory optimization using Mixed-Integer Linear Programming. The purpose of the extension is to ensure that avoidance constraints are respected at all times between discrete samples, not just at the sampling times themselves. The method is very simple and involves applying the same switched constraints at adjacent time steps. This avoids the large numbers of extra constraints introduced by the existing approach. A key benefit of efficient inter-sample avoidance is the facility to reduce the number of time steps without having to compensate by enlarging the obstacles. Hence coarse discretizations can be adopted to reduce computation time without compromising on feasibility of the solution. These possibilities are illustrated in both obstacle avoidance and multi-vehicle separation scenarios. A further extension to the principle is presented to account for curved paths between samples, proving useful in cases where narrow passage-ways are traversed.

(A brief paper on this topic has also been submitted to the International Journal of Robust and Nonlinear Control.)

3.3 Demonstrations

The Multi-Sector Controller (MSC) demonstration platform was shown to three members of the R&D team at NATS on a visit to Bristol in early 2013. This included an example scenario and the application of several of the constraint tools developed during the project, illustrating their effect on the behaviour of the optimizer and the resulting trajectories. More details of the demonstration can be found in [4]. The visit did not comprise a formal component of the SUPEROPT project but was exploited for dissemination and to gain feedback on the work.

The NATS representatives were positive about the way SUPEROPT enabled a “gentle” introduction of optimization into ATM systems at low levels of automation, enabling experience to be gained in the potential of these methods without the need for a high-risk leap to a fully automated approach. They had a number of questions about possible extensions, leading to some additional features in later prototypes [4]. The discussion raised interesting implications about SUPEROPT’s adoption of multi-aircraft cooperative resolutions, which are difficult to reconcile with the current practice of considering one “subject aircraft” at a time. Thus considerable human factors work has been identified in the process of exploiting the natural cooperative capabilities of multi-vehicle trajectory optimization. Finally they were impressed with the capability to avoid knock-on conflicts and effects.

3.4 Exploitation plans

- A journal paper submission is under preparation covering all the major results of SUPEROPT
- An internally funded PhD project started in January 2013 which will exploit some of the ideas and tools from SUPEROPT to study cooperative decision-making in ATM
- The University of Bristol is having on-going discussions with NATS regarding a potential collaboration based on SUPEROPT looking at uncertainty in trajectory optimization.

4 Total Eligible Costs

This section is based on the Project Costs Breakdown Forms of the eligible costs incurred by project participants.

Date	Deliverables on Bill	Contribution for Effort	Contribution for Other Costs (specify)	Status
30/10/2012	D0.0, D1, D0.1	€16160.62	€2456.50 (travel)	Paid
20/11/2012	D0.2, D2A, D3A, D0.3	€58687.48	€331.13 (travel)	Paid
TBA	D0.4, D2, D3, D4, D0.5	€77000 (TBC)	€2000 (travel, TBC)	To be billed
TOTAL		€152000 (TBC)	€4800 (TBC)	

Table 2 Overview of Billing

Company	Planned man-days	Actual man-days	Total Cost	Total Contribution	Reason for Deviation
University of Bristol	295	294	€152000 (TBC)	€152000 (TBC)	N/A

Table 3 Overview of Effort and Costs per project participant

5 Project Lessons Learnt

What worked well?
The evolution, in conjunction with EUROCONTROL, of the two Case Studies – Multi-Sector Area and Network Manager – helped focus the project, even though we later had to narrow focus even more and concentrate just on the first case.
The opportunity for the project leader to attend GENSPACE gave a valuable boost to the ATM context awareness of the project.
Our discussions with NATS near the end of the project provided valuable ideas and feedback, for example on additional capabilities to study and on ways to exploit the new tools.
The relatively loose scope of the project enabled us to follow the innovations as they emerged, without being tied to a restrictive programme of work.
The overall conclusion of the project is positive, in that the potential for supervision of optimizers has been shown, and a number of simple but useful interfaces have been developed.
What should be improved?
A more thorough evaluation would have been desirable, with input from persons with operational experience and a potential second stage re-evaluation after a chance to address their comments. SUPEROPT was unable to get access to such people.
Since trajectory optimization goes beyond the human-centred notion of working with one subject aircraft at a time, studies into the human factors implications of multi-aircraft cooperative conflict resolution are motivated.
A second GENSPACE experience would have been beneficial, to enable the researcher to attend this very useful course.
Discussion of automation within WP-E, e.g. at ATACCS, is almost exclusively focussed on human factors issues associated with its introduction. This is undoubtedly an important topic, but the potential performance benefits of automation should also be emphasized. Innovations ought to be looked at in terms of potential as well as difficulty of implementation.
SESAR's financial and effort reporting and invoicing processes are unduly onerous. Each stage of the project – proposal; planning; progress reporting; invoicing; gate review; and this final report – has required the effort and cost to be broken down and reported in a different way. The cost breakdown form spreadsheets have bugs and infinite loops in their macros. It's not clear if the added value of this oversight outweighs the cost of administering it, if any value is added at all.

Table 4 Project Lessons Learnt

6 References

[1] SUPEROPT, "Problem Definition and Literature Review", E.02.01-D1, March 2012.

[2] SUPEROPT, "Optimizer Algorithms for Supervisory Control: Enabling Supervisor Input", E.02.01-D2-1.1, December 2012.

[3] SUPEROPT, "Optimizer Algorithms for Supervisory Control: Informing the Supervisor", E.02.01-D3-1.1, December 2012.

[4] SUPEROPT, "Supervision of Trajectory Optimizers", E.02.01-D4-1.1, May 2013.

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[6] PHARE, "Project Website – Concepts – Multi-Sector Planning", visited March 2012, [Online], Available: http://www.eurocontrol.int/phare/public/standard_page/MSP.html

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[8] Richards, A. Constraining the Sense of Conflict Resolution: Supervision of Route Optimization, First SESAR Innovation Days, 2011

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[10] Turnbull, O. & Richards, A. 4-D Trajectory Optimizers for Conflict Avoidance Using Speed Advisories, Tenth USA/Europe Seminar on ATM R&D (to appear), 2013

[11] Turnbull, O. & Richards, A. Collocation Methods for Multi-Vehicle Trajectory Optimization, European Control Conference (to appear), 2013

[12] Richards, A. & Turnbull, O. Inter-Sample Avoidance in Trajectory Optimizers using Mixed-Integer Linear Programming, AIAA Guidance Navigation and Control Conference (to appear), 2013