Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2001-360

Robust and Efficient Autopilot control Laws design

Publishable Synthesis Report

May 1, 1998 - October 31, 2000

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This investigation has been carried out under a contract awarded by European Commission, contract number BRPR-CT98-0627, and partly as a part of NLR's basic research programme. Workplan Number V.1.A.1
European Commission has granted NLR permission to publish this report.

Division:	Flight
Issued:	August 2001
Classification of title:	Unclassified

Robust and **E**fficient **A**utopilot
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June 28th, 2001

BRPR-CT98-0627/PSR-01v1

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Contract N°: BRPR-CT98-0627
Project N° : BE97-4113
Start date : May 1, 1998
Duration : 30 months

NLR	National Aerospace Laboratory (project co-ordinator)	(NL)
AS	EADS Airbus SA, Toulouse	(FR)
DA	EADS Airbus GmbH, Hamburg	(DE)
DLR	Deutsches Zentrum für Luft- und Raumfahrt	(DE)
DUT	Delft University of Technology	(NL)
ONERA	Office National d’Études et Recherches Aérospatiales	(FR)

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Version : v1
Completed : 28/06/2001

Project co-ordinator: W.F.J.A. Rouwhorst

Acknowledgement

The Final Technical Report of the REAL project was a joined effort under responsibility of the Project Management Team. The report’s main editors were W.F.J.A. Rouwhorst and M. Selier. All those who contributed are kindly thanked for their efforts made.

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Contents

(66 pages in total)

List of Abbreviations

ADFCS	Affordable Digital Flight Control Systems
AFCS	Automatic Flight Control Systems
AS	Aérospatiale-Matra Airbus
ATTAS	Advanced Technologies Testing Aircraft System
AWO	All Weather Operations
CEC	Commission of the European Communities
DA	European Aeronautic Defence and Space Company Airbus GmbH
DI	Dynamic Inversion
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DP	Design Process
DUT	Delft University of Technology
FCL	Flight Control Laws
GS	Glide Slope
JAR	Joint Aviation Requirements
LOC	Localiser
MC	Monte-Carlo
MIMO	Multi Input Multi Output
MOPS	Multi-Objective Parameter Synthesis
MTA	Mid Term Assessment
NLR	National Aerospace Laboratory
ONERA	Office National d’Études et Recherches Aérospatiales
PD	Proportional and Differential
PMC	Project Monitoring Committee
PMT	Project Management Team
REAL	Robust and Efficient Autopilot control Laws design
RealATTAS	ATTAS model for the REAL project
RealCAM	Real Civil Aircraft Model
RTW	Real Time Workshop
SIMPA	Simulation Pilote Automatique
SIMPALE	SIMPA “Light Edition”
SISO	Single Input Single Output
TECS	Total Energy Control System
THCS	Total Heading Control System
WP	Work Package

1 Summary

This document contains a description of the REAL project (Robust and Efficient Autopilot Control Laws design). The project was carried out in the fourth Framework Program of the Commission of the European Communities (CEC). A detailed description of the technical achievements is given in the Final Technical Report [FTR01]. Exploitation and dissemination aspects are treated in more detail in the Exploitation Report [ER01].

In the REAL project, it was investigated how modern robust control design methods may improve the efficiency of the autopilot design process. First the current industrial autopilot design process was described and potentials for improvement were identified. Then two separate design teams each developed a control laws design process, using modern robust control methods and automation concepts. With these processes, each team designed autoland control laws for two benchmark problems:

- The **RealCAM** benchmark, which was used to set up the process and to demonstrate the robustness of the designs. For the robustness assessment, EADS Toulouse's certification tool SIMPA (Simulation Pilote Automatique) was used.
- The **RealATTAS** benchmark, which was used to demonstrate the efficiency of the design process and to demonstrate that the resulting control laws can be implemented into real-time flight computers. This was proven by flight tests on DLR's flying testbed ATTAS.

Industry evaluated the controller performance concerning robustness and the efficiency potential of the proposed design procedures. A main result is that both investigated robust design methods have proven to be very powerful in designing realistic robust controllers for an autoland system of a civil aircraft and have good potential for industrial application.

Structure of this report

In Chapter 2 the project consortium, the industrial relevance of the project and the project structure are introduced. Chapters 3 to 6 describe the technical results achieved within the project: from economical benefits study to actual autoland designs, flight tests and industrial evaluation. In Chapter 7 the results are synthesised and conclusions and recommendations are given. Finally, exploitation and dissemination aspects are dealt with in Chapter 8. A list of project deliverables can be found in Appendix A.

2 Introduction

2.1 Industrial Objectives and Strategic Importance

The current development process for autoland systems of civil airliners contains a time-consuming trial-and-error approach to design the control laws. This trial-and-error approach is necessary to achieve closed-loop system robustness against all possible variations of airports, atmospheric and aircraft characteristics that influence the performance. Furthermore, design requirements imposed on the performance of an autoland system have to be fulfilled and it has to be proven to the certification authorities that the system meets their performance and safety requirements, like e.g. JAR-AWO, see [JAR96]. Typically, design models are improved multiple times during aircraft development and controllers have to be redesigned if they are not robust against parameter changes of the model.

Currently, autopilot robustness is addressed by both design techniques and simulation techniques. Safety implications are assessed during the early design phase by statistical analysis, using for instance Monte-Carlo simulation techniques. However, much effort is needed to tune the controller to achieve the required performance and robustness, and to fulfil the safety requirements. The controller design would be more efficient if the synthesis method could directly address the requirements, performance and robustness demands. Therefore, the main question to be answered in the REAL project is: "*How can advanced design and synthesis methods help the engineer to more efficiently establish robust and safe controllers for Cat III autoland systems of civil airliners?*"

The answers to this question are of strategic importance to the aerospace industry, because the general opinion is that it should become easier to design for (and validate) autoland system changes, for instance related to aircraft type modifications. Furthermore, the assessment tools set up will have to facilitate the process of acceptance by the certification authorities. This saves non-recurring cost and will reduce the time-to-market, thus strengthening the competitive position of the European aerospace industry in the world.

2.2 The Project Consortium

The project consortium consisted of six organisations in France, Germany and the Netherlands.

• NLR	National Aerospace Laboratory (project co-ordinator)	(NL)
• AS	EADS Airbus SA, Toulouse	(FR)
• DA	EADS Airbus GmbH, Hamburg	(DE)
• DLR	Deutsches Zentrum für Luft- und Raumfahrt	(DE)
• DUT	Delft University of Technology	(NL)
• ONERA	Office National d'Études et Recherches Aérospatiales	(FR)

A short description of the organisation as well as address information are give below:

NLR – project co-ordinator

NLR is an independent, non-profit research institute partly funded by Dutch government. It gives support to the national and international Aerospace Industry, Civil and Military operators, government agencies and other organisations concerned with aeronautics and space flight. The scope of the REAL project fits well with the corporate strategy of the NLR to be able to provide this type of support.

EADS-Airbus Toulouse (AS)

AS is part of EADS, the European Aeronautic Defence and Space company, Europe's premier aerospace company. EADS comprises the activities of the founding partners Aerospatiale Matra S.A. (France), Construcciones Aeronáuticas S.A. (Spain) and DaimlerChrysler Aerospace AG (Germany), the latter referred to as DA in this report, see below. In terms of market share EADS is one of the top manufacturers of commercial aircraft, helicopters, commercial space launchers and missiles. EADS is also a leading supplier of military aircraft, satellites and defence electronics. AS is responsible for the design and certification of all Airbus aircraft (e.g. A300, A310, A320, A330/340 families) including the new A380 aircraft.

EADS-Airbus Hamburg (DA)

DA is also part of EADS, the European Aeronautic Defence and Space company, Europe's premier aerospace company. DA has a high interest in improving the efficiency of its current design processes.

DLR

DLR is the German national organisation for aerospace research and development. The main research areas are aeronautics, space flight, energy technology and transport technology.

The Institute of Flight Mechanics in Braunschweig is working on system identification, aircraft handling qualities, modelling of aircraft and new flight control concepts with respect to reconfiguration. They operate the in-flight simulator ATTAS (Advanced Technologies and Testing Aircraft System), which is very well suited to evaluate flight control systems under realistic conditions.

The control design engineering department of the Institute of Robotics and Mechatronics at DLR Oberpfaffenhofen has expertise in the fields of control systems design for aerospace applications, object-oriented modelling and simulation for multi-physics systems, as well experience in multi-criteria/multi-model design optimisation.

Delft University of Technology (DUT)

DUT is the main institute in the Netherlands for academic education of aeronautical engineers. Research and education by the Control and Simulation Division cover dynamics and modelling of aircraft and spacecraft, design and analysis of advanced control systems, flight and wind tunnel testing, flight simulation, design and analysis of man-machine interfaces and air traffic management. The Control and Simulation Division co-operates with universities and research institutions from all around the world to exploit the increased possibilities of joined forces. The division is actively involved in research programs to let industrial partners apply and commercialise the results of contract research.

ONERA

ONERA is the French aeronautics and space research institute. It gives support to the national and international Aerospace Industry, Civil and Military operators and government agencies. The scope of the REAL project fits well with the competence field of ONERA.

2.3 Focus of the Project

Since it is not possible to perform an entire autopilot design in the course of the project it was decided that the design activities should focus on the autoland design. To be even more specific, it was decided to consider only the approach and flare, until touchdown of the main gear. Thus the ILS capture and roll-out phases of autoland were not considered.

These tasks were selected since robustness is of extreme importance in the autoland mission. The aircraft must land very precisely for different values of landing weight (approach speed) and centre-of-gravity location, while subjected to variations in terrain, runway slope, wind speed and direction, turbulence, sensor and ILS noise.

2.4 Structure of Project Activities

The project had three main streams of activities:

1. First, a report was written on the current Industrial Autopilot design process, wherein also the possible benefits of the use of modern design techniques are indicated. This description has been the basis for the autoland design activities on two benchmark models.
2. During the first design, for the RealCAM (Real Civil Aircraft Model) benchmark, each of two design teams have developed a design process based on advanced synthesis techniques which should result in a robust controller. These controllers were thus evaluated mainly on **robustness** properties, using the industrial evaluation tool “SIMPA” from AS.
3. The objective of the second design was to demonstrate the **efficiency** of the process and applicability of the methods to a real world problem. Each design team reapplied the same design process to develop an autoland controller on a model of DLR’s ATTAS aircraft (the

RealATTAS benchmark) in a short time. This controller was implemented in the actual ATTAS aircraft and flight tested.

The three activities were executed under two project phases. A global view on these project phases is presented in Figure 2-1.

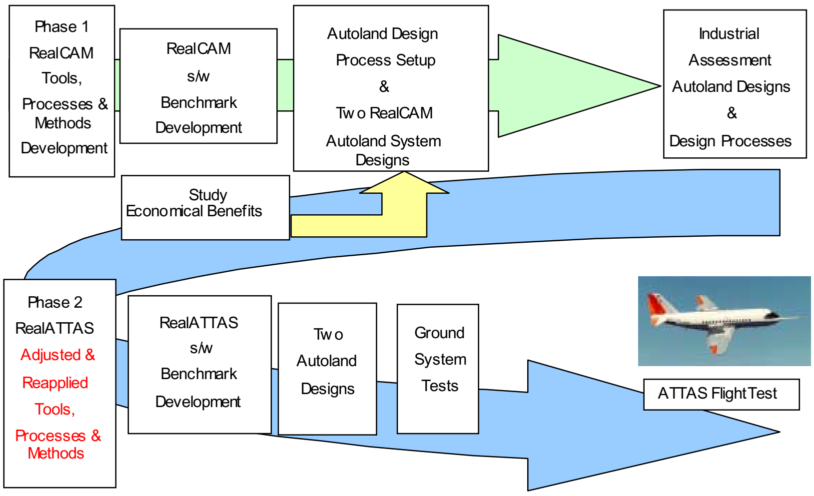

Figure 2-1 REAL project phases

3 Technical Achievements: Economical Benefits study

An economical benefits study was conducted at the start of the project. The objectives of this study were:

1. To write a report „Autopilot Design Process Study“. This report was set up for educational purpose and was a reference for the REAL design teams, which came from research institutes. It should enable the design teams to address realistic industrial requirements. The study had a general nature and would not relate to any current aircraft project.
2. To provide guidelines for the design teams how to address cost benefits of their proposed design process.

3.1 Autopilot design process study

Based on a literature study and inputs from AS, the history and current state-of-the-art of Automatic Flight Control Systems (AFCS) has been described. The various autopilot functions and modes have been surveyed and piloting procedures in low visibility operations are explained, taking Airbus and Boeing aircraft as examples.

Then, a generic, state-of-the-art Flight Control System design process is described by means of the so-called V-model. For the Flight Control Laws (FCL) design process, which is a part of the FCS design, a mini-V model has been given. The FCL design process has a highly iterative nature of designing (synthesis) for the nominal case. Performance and robustness with respect to parameter variations and uncertainties is verified using a statistical analysis (Monte-Carlo approach).

The requirements for an advanced design process have been derived. The design process can be divided into four phases:

1. the off-line design,
2. pilot-in-the-loop testing in the development flight simulator,
3. Iron bird testing (hardware-in-the-loop),
4. Flight testing.

The costs of one iteration in each design phase increase exponentially. To reduce the overall costs of the design, it is clear that the number of iterations in the last three design phases should be reduced, i.e. the design should be “good enough” after the first (offline) design phase, see Figure 3-1.

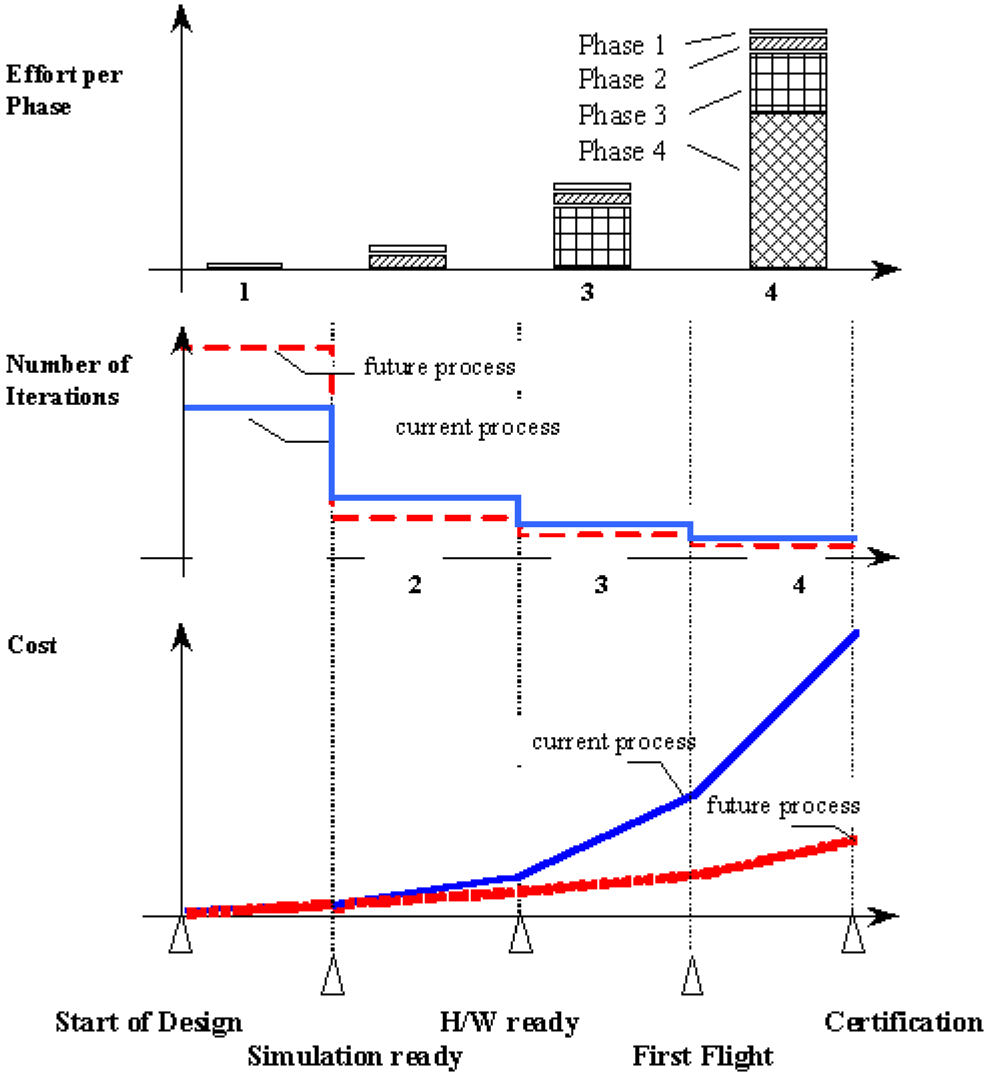

Figure 3-1 Comparison between effort and costs of the current and a future design process

The potential benefits of the use of modern control design techniques are identified. The modern control techniques are able to take into account the various parameter variations and uncertainties directly in the first design phase, thus saving costly iterations in the late project phases.

3.2 Typical Aspects of the Industrial Autoland Control Laws Design Process

Based on industrial experience from DA, AS and experts of the former Fokker aircraft factory, the specific aspects of the autoland design process have been identified. Essentially the design process for autoland systems does not differ substantially from the generic AFCS design procedure and from the generic FCL design process mentioned above. However, some typical aspects have been identified and reported. Most of these aspects are the result of two main differences with the general autopilot design:

1. An autoland system is flight critical and has to be fail operational. This means that if a failure occurs, there should be sufficient redundancy in the system to continue the operation. The other parts of the autopilot are mostly fail-passive, which means that if a failure occurs, control is given back to the pilots. The larger degree of redundancy required for fail operational systems has consequences for the design.
2. An autoland system has to be validated for a wide range of operating conditions. For this wide range it must be proven in a statistical way that the designed controllers meet the performance and robustness requirements.

The results of this work (Deliverable D2), are a report TP-02 and an addendum report TP-02A, see Appendix A.

4 RealCAM activities

4.1 Objectives

The objectives of the RealCAM activities were:

- To develop an advanced design process for the design of autoland systems, using modern robust control techniques,
- To design a controller with this process that has good performance and which is sufficiently robust against parameter variations and parameter uncertainties which an aircraft may encounter.

4.2 RealCAM benchmark definition

A RealCAM (Real Civil Aircraft Model) benchmark has been developed. It consists of a complete user friendly MATLAB software shell and document with a detailed description of the model, tools etc.

The control problem has been defined by explaining the autoland mission to be flown and design requirements from the aviation authorities and from industrial practise have been given. The model, a large civil transport aircraft has been described. This model is a simplified version of a model implemented in AS's robustness analysis tool SIMPA. Tools were developed for evaluation of the aircraft's dynamics and evaluation of the controller performance. Also, guidelines were developed on how the design teams should report their designs, and how the efficiency of the design processes would be assessed.

For certification of an automatic control system, industry (AS) uses the simulation tool SIMPA. This tool (among others) performs Monte-Carlo simulations of the closed-loop system to assess the robustness of output variables against variations on input parameters. For the purpose of the REAL project the Light Edition of SIMPA (SIMPALE) has been developed by ONERA for Matlab/Simulink. It takes only the CAT-III autoland requirements into account and is based on RealCAM, the simplified version of the full aircraft model used in SIMPA. This tool is very efficient; it performs a robustness analysis of 2000 landings with varying parameters within 15 minutes on a Sun SPARC Station Ultra 5 270 MHz. SIMPALE can also be run efficiently on a PC/laptop computing environment. Due to this speed, it enables the engineer to rapidly iterate the design of a controller and analyse its robustness.

The results of the RealCAM benchmark work (Deliverable D1.1) are report TP-01 and a software shell, the so-called RealCAMShell, see Appendix A.

4.3 RealCAM autoland predesign

The main objective of the RealCAM predesign was to check the RealCAM benchmark definition and the software and to make it sufficiently error free. Thus the objective was not to design a perfect controller which satisfies all autoland requirements, although the predesign could have been used by the design teams to identify difficult tasks of the design. The controller used conventional design methods for the inner loops, conventional controller structure for localiser tracking and the methods Total Energy Control System (TECS) and Variable Tau for glide slope tracking and flare respectively.

The resulting controller, largely based on classical design, proved to be not sufficiently robust. This again indicates the difficulty of the task of designing a robust controller with classical techniques when there is not much time for iterations.

Unfortunately the predesign controller structure and the software set-up could not form a basis for ONERA and DLR to set-up and develop their sophisticated designs. The methodologies and tools used in the predesign prevented this. In future project such a potential project efficiency aspect should be given more thought.

The predesign work was reported in TP-03. Also controller software is available, see Deliverable D3.1 in Appendix A.

4.4 Autoland Design Process I: ONERA

4.4.1 Overview of the Design Process

ONERA made use of the Multi-model Eigenstructure Assignment method.

As shown in Figure 4-1, the ONERA design process starts with the definition of a general controller structure. This is a fundamental step, which requires a certain amount of experience and expertise. This step is the most problem dependent one in the design process. After the structure has been defined, a synthesis model may be easily built and the linear design (which can be viewed as a sub-process) can be applied. In the ONERA approach, the feedforward design appears as a parallel task on which it will be necessary to iterate according to the simulation results.

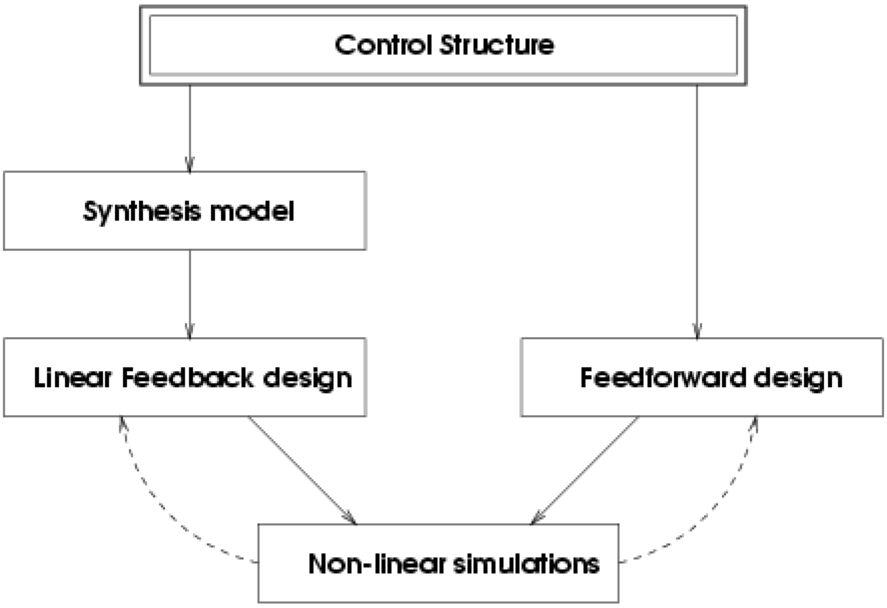

Figure 4-1 Overview of the ONERA design process

4.4.2 General Controller Structure Definition

This controller structure, as shown in Figure 4-2, consists of two main parts with nonlinear signal processing on one hand, and linear gains on the other hand. The linear gains result from feedback and feedforward design and will be discussed further. As for the nonlinear part, it can also be split into two blocks. The first one, which is called the *input signals processing block* is the most important one. The aim of the second block is to perform a "post-treatment" on the control outputs coming out from the linear feedback gains. This treatment simply consists of adding trim values to the control signals. If necessary, bounding functions (position and rate) may also be included in this block. In the particular case of autoland control design, a specific treatment is performed on the thrust command. As a matter of fact, when the aircraft lands it is necessary to make sure that the engines are near "idle" position to allow the activation of the reverse mode after touchdown.

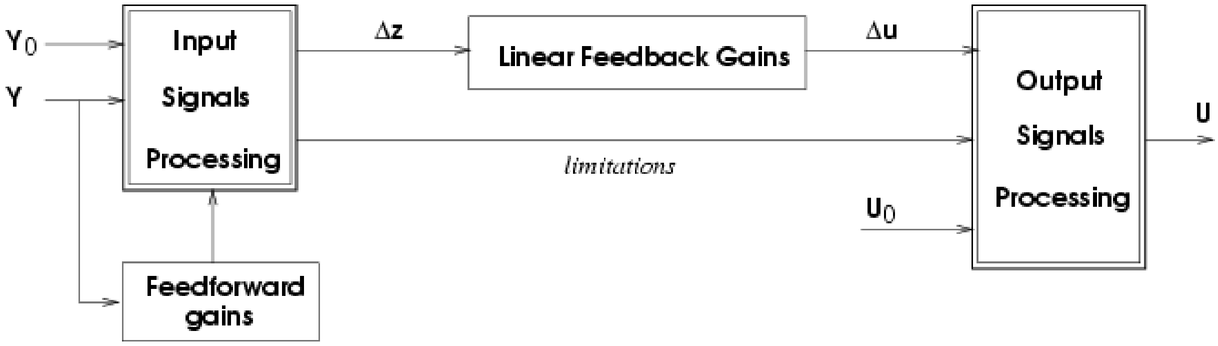

Figure 4-2 General controller structure definition

4.4.3 Design Process

The strategy that is used in the Multi-model Eigenstructure Assignment method is the same for longitudinal and lateral controller design. The main steps are detailed now.

Step 1- Choose an architecture including choices relating to

- integrator locations to insure tracking to some extent,
- which measurement signals are available for inner loop design,
- feed-through signals (*e.g.* estimate of touchdown distance, trajectory profiles,...),
- reject disturbances to some extent by (complementary) filtering,
- switching strategy (from approach to flare, from approach to decrab).

Clearly, at this stage, some design specifications are already considered and satisfied to some extent. This stage is essential because bad choices would lead to unfeasible designs at the next steps.

Step 2- Compute an initial inner loop design (including inner feedback and inner feedforward). As design specifications are global, there is no inner loop specification. So, an initial inner law is computed by trying to reproduce a closed-loop aircraft as close as possible to the open-loop aircraft but with improved stability and less cross-coupling. More precisely, the free parameters are chosen in order to assign closed-loop eigenvalues selected from open-loop values. For example if $-0.1+5\,j$ is the open-loop value, it is shifted to $-5+5j$ in closed-loop and so on. The remaining free parameters (eigenvector selection) are chosen in order to ensure decoupling properties (in the lateral case decoupling is performed relative to the lateral acceleration per g and the bank angle, in the longitudinal case decoupling is performed relative to the vertical load factor and the air speed).

Step 3- It remains to tune the inner loop considering the global design specifications. As eigenvectors are automatically selected for given desired eigenvalues, only the choice of desired eigenvalues needs to be treated in order to fulfil the performance objectives (those that are not already met by the chosen architecture or eigenstructure selection). Usually it suffices to move globally all the eigenvalues for reaching a good compromise.

Step 4- This step aims at scheduling the feedback so that the performances obtained at step **3** remain valid in the entire flight envelope. The nominal design of step **3** is automatically repeated on a grid of linearized aircraft aerodynamic models. The resulting gains are interpolated.

Step 5- In the case where no solution is found at step **3**, the architecture is enriched. This has been the case for example on the lateral axis outer loop design. It was easily shown that the required performance could not be achieved with a simple gain on the lateral displacement. A derivative term had to be introduced. As a consequence, the architecture had to be modified to provide the linear outer loop with a “noise-free” derivative signal, which was done by using complementary filters to combine lateral displacement and track angle.

4.5 RealCAM Autoland Design I: ONERA

Robustness was one of the major issues of this project. As robustness was not difficult to achieve in the lateral case, only the longitudinal results are briefly presented. After steps **2** to **4** of the design process were performed, a very robust inner law was obtained as illustrated in Figure 4-3 and Figure 4-4. Figure 4-3 shows that for a set of relevant linearized models, the time responses are very similar (only the cross coupling differs but sufficiently low). Figure 4-4 shows that the closed-loop poles have little sensitivity to aircraft model variations.

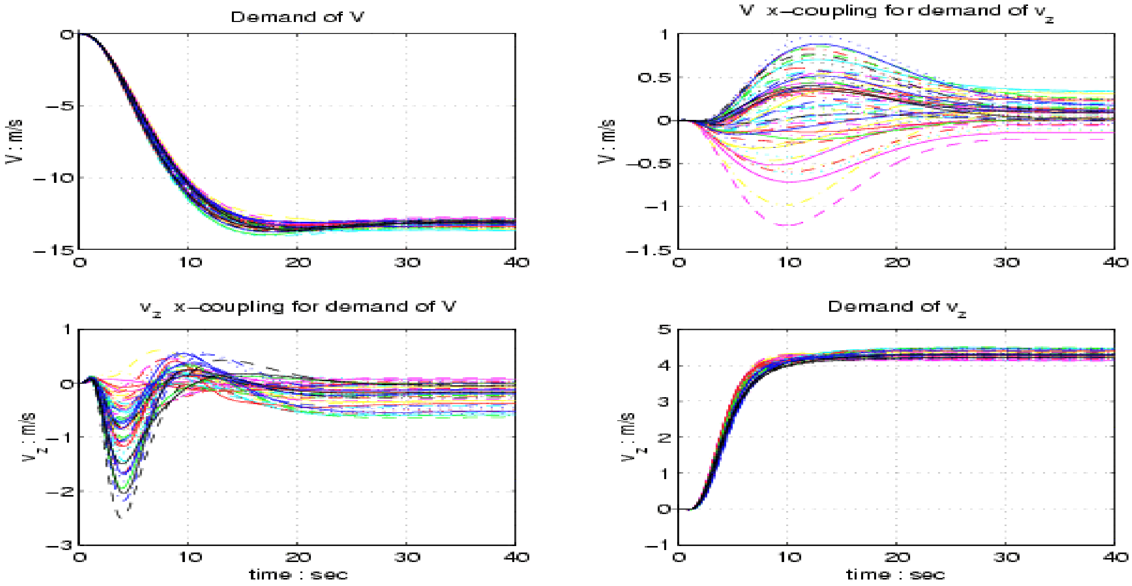

Figure 4-3 RealCAM - Longitudinal inner loop assessment (time responses)

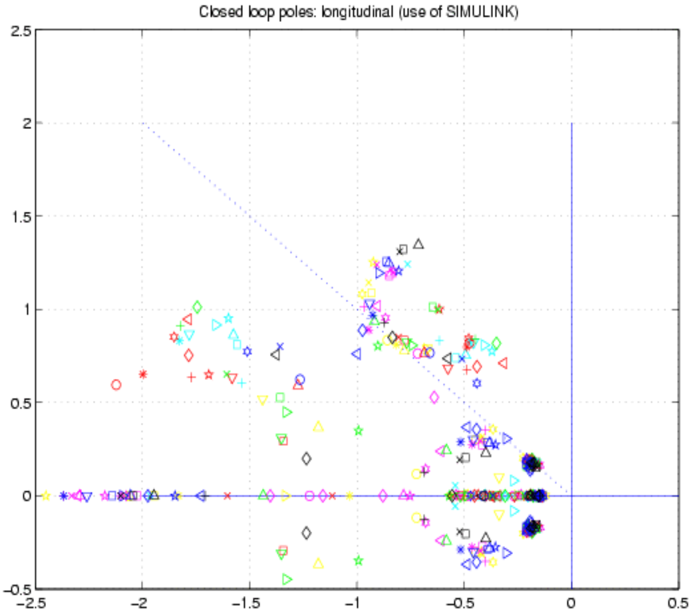

Figure 4-4:RealCAM - Longitudinal inner loop assessment (pole map)

Steps **1** and **5** correspond to the architecture selection for integration of the inner loop. These steps appeared to be more difficult than those related to achieving robustness. After having enriched several times the architecture (see description of step **5**), most of the design objectives were met as shown in Figure 4-5. This figure corresponds to a SIMPALE Monte-Carlo type of evaluation with aerodynamic and inertial uncertainties. Simulations are performed with turbulent wind. It shows in the upper left part that the probability to land too short (evaluated by HTP60, the wheel height 60m after the runway threshold), is very small (even smaller than the specification of 10^{-5}). The probability to land too long (evaluated by XTP in the upper right part), implying landing further away than 915 m after runway threshold, lies between 10^{-4} and 10^{-5} which is slightly higher than allowed. The vertical speed at touchdown (VZTP) is also displayed to evaluate the risk of hitting the ground too strongly. The associated plot reveals that the probability for VZTP to be higher than 10 ft/sec (3,048 m/s) remains smaller than 10^{-6} (as required).

These simulations also reveal very good robustness of the lateral control system. As a matter of fact, despite the uncertainties the lateral deviation of the midpoint of the main landing gear at touchdown (YTP) remains statistically much smaller than required. The same observation holds for the bank angle (PHI) and the slide-tire angle at touchdown (SSTP).

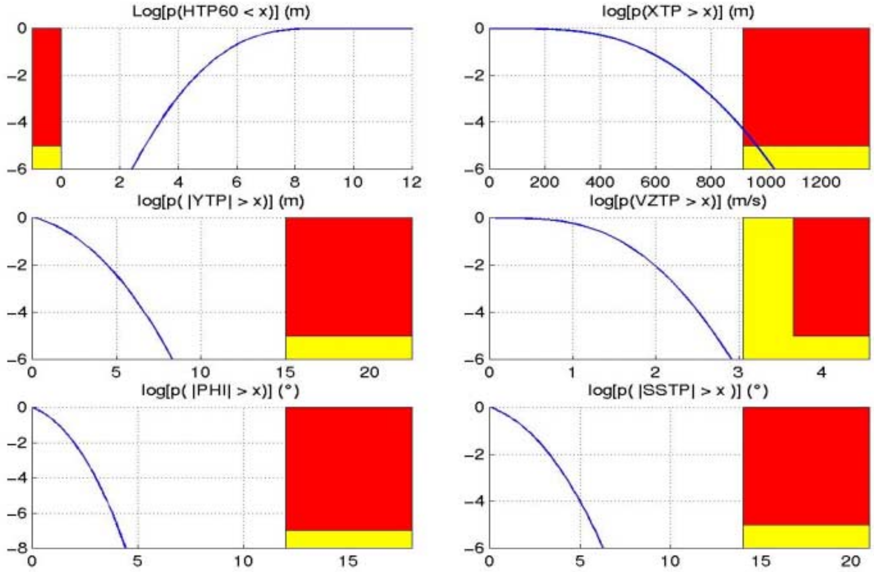

Figure 4-5: RealCAM - Aerodynamic and inertial uncertainties (cumulative distributions)

The ONERA design results were issued in combined Deliverable D3.2a/D4.1a, which consists of a report and the controller software. See Appendix A.

4.6 Autoland Design Process II: DLR

The DLR design process is based on a Multi-model, multi-objective optimisation of free parameters within a (nonlinear) controller architecture that is specified by the designer. Performance objectives are formulated using computational criteria that may be derived from linear analysis (e.g. stability from eigenvalues) as well as from nonlinear analysis (e.g. rise time from nonlinear simulation time responses). Robustness is addressed globally via a multi-model approach, and locally via criteria in the optimisation loop (e.g. gain/phase margins). The overall design process is depicted in Figure 4-6. The principal steps (in the block diagram to the left) and the supporting software tools (to the right) will be explained in the following subsections. The process and software tools (except the newly developed SIMPALE) have been successfully used in numerous aerospace and robotics applications.

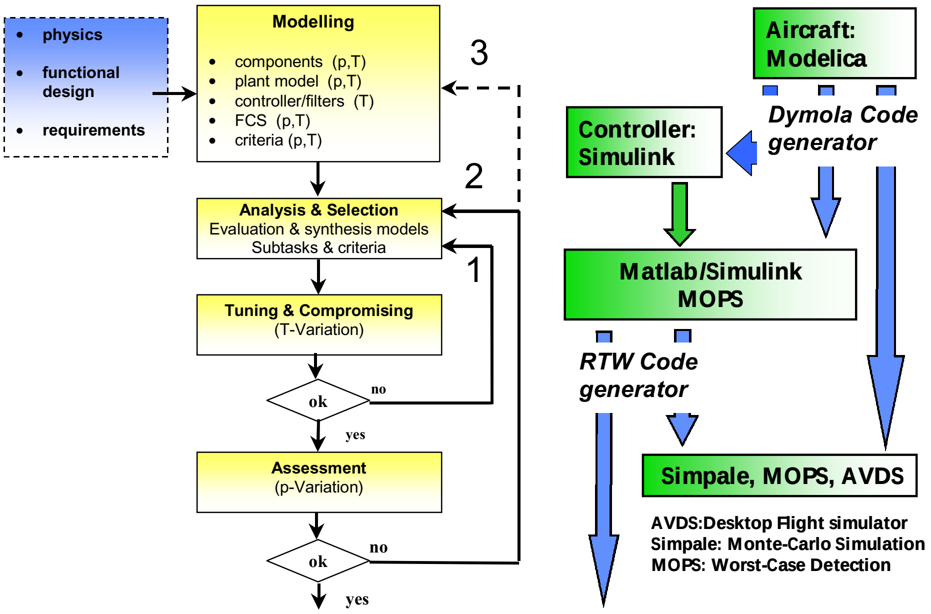

Figure 4-6: DLR design process with supporting synthesis and analysis tools.

4.6.1 Modelling

Plant model. For analysis and design computations, parameterised models of the aircraft dynamics are required. As a modelling platform, the object-oriented modelling software Modelica/Dymola [Elm93] is used, in which a flight-mechanics class library [Moo99] is available. Within Dymola, the model is composed and processed symbolically. Simulation code can be generated automatically for several engineering environments. Within the REAL-project, the RealCAM and the RealATTAS models were implemented and simulation code was generated for use in the Matlab/Simulink based benchmark software (see sections 4.2 and 5.2).

Controller model. Controller architecture selection and controller parameter tuning are fully independent. The controller is selected by the designer and therefore open to incorporate all available knowledge and experience. The controller architecture may be nonlinear and is usually specified in Matlab/ Simulink. Within the REAL project, the Simulink add-on Real-Time Workshop (RTW) was used for automatic code generation, allowing for implementation in SIMPALE and, after the design had been finalised, for implementation in SIMPA (RealCAM controller) and ATTAS (RealATTAS controller).

Requirement or criteria models. For parameter tuning within the given controller structure, multi-objective parameter optimisation is employed. This approach requires the formulation (modelling) of the design requirements as quantitative mathematical criteria. In most cases this is a simple task, because requirements are already formulated mathematically. Criteria computation is done in Matlab macros from nonlinear and/or linear closed-loop analysis.

4.6.2 Analysis and Selection

The analysis involves exploring the open-loop aircraft dynamics over different flight conditions and parameter combinations (by varying model parameters *p,* see Figure 4-6) using nonlinear simulations and linear analysis. The aim is to select representative points for use in multi-model based controller parameter tuning and compromising.

A complex design task, like autoland control law design, has to be split into several sub-tasks. For REAL, this was induced by the adopted modular controller architecture. Sub-tasks for inner loops, flight path tracking loops, guidance modes (glide slope and localizer), flare law, and line-up mode were defined. For these sub-tasks the appropriate models, manoeuvres, disturbances and design criteria were selected and macros for computation were written.

4.6.3 Tuning and Compromising

Tuning & compromising is based on a multi-criteria/multi-model parameter tuning facility which provides a systematic way for optimisation based control law tuning by directly specifying bounds and demands on design specifications and flying/handling qualities as well as physical control realisation constraints [Joo99]. Robustness to variations in model parameters and operating conditions is covered basically by the multi-model formulation. For a given controller structure, the free parameters of the controller, *T*, are automatically tuned by an optimiser to their best values satisfying the specifications and flying/handling quality demands. The multi-objective tuning of parameters is achieved by using the optimisation tool MOPS (Multi-Objective Parameter Synthesis) [Joo99].

During optimisation, intermediate results are visualised. All scaled criteria values are displayed using parallel co-ordinates, see Figure 4-7, in which each arrow represents an optimisation criterion. The optimisation objective is to arrive at the condition that all criteria are below the horizontal line in Figure 4-7.

Visualisation of intermediate analysis results (simulation responses, eigenvalues, etc.) may be specified by the user as well.

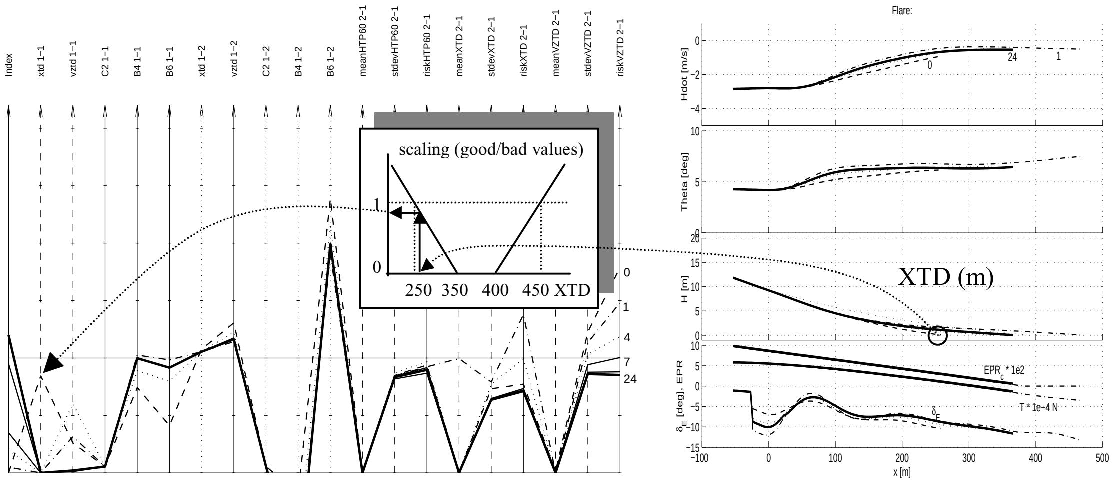

Figure 4-7: On-line visualisation of flare law criteria via parallel co-ordinates (l), and nonlinear simulation results (r). Example: criterion XTD = touchdown point from runway threshold

4.6.4 Assessment

The purpose of the assessment is to detect hidden weaknesses in the designed controller. Usually systematic grid-based parameter studies or Monte-Carlo simulations are performed where a large number of parameter combinations and different operating conditions have to be examined. A more efficient way is to search for worst-cases by parameter optimisation, i.e. for given designed tuner values T^* the worst-case model parameters p^* are searched such that a selected performance criterion, e.g. stability, is as bad as possible. Worst-case models may serve to update the set of multi-models used for tuning & compromising (loop 2). Assessment is usually performed within the MOPS environment with its visualisation features. Of course, any other assessment tool can be used. In the REAL project Monte-Carlo analysis was applied by means of SIMPALE.

4.6.5 Design Process Cycles

The proposed design process is an iterative procedure, as indicated by the three different iteration cycles in Figure 4-6. Cycle 1 mainly involves adjustment of criteria properties (scaling, type) to steer the optimisation, cycle 2 mainly involves updating the selection of multi-models in case the assessment indicates that the design lacks robustness at some point, cycle 3 involves modifying the controller architecture in case the structure turns out to be deficient.

4.7 RealCAM Autoland Design II: DLR

4.7.1 Controller Architecture

The first step in the DLR autoland controller design was the selection of the architecture. In the DLR design process, this is done independently from control law optimisation and performed as a modelling task (Figure 4-6). The global structure is depicted in Figure 4-8.

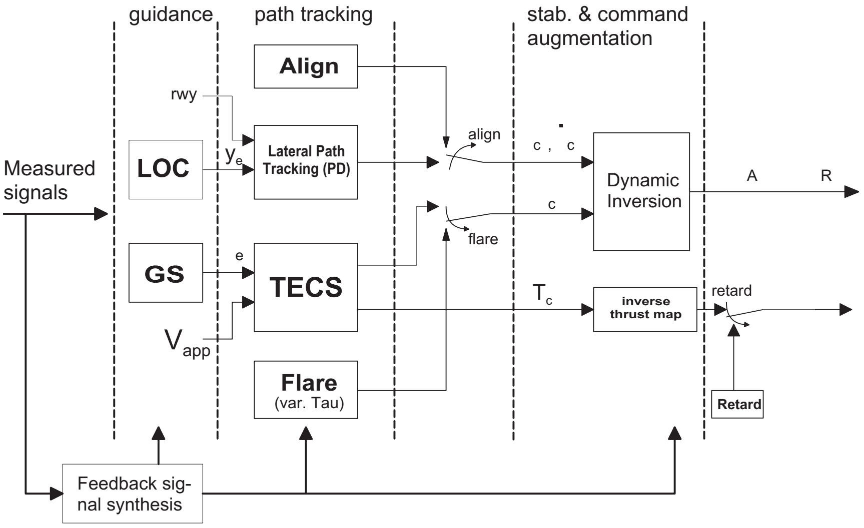

Figure 4-8: DLR autoland controller architecture.

Three main loops can be identified, separated by the vertical dashed lines: stability and command augmentation, path tracking, and guidance. The task of the inner loops is to improve stability and to achieve robust tracking of inner loop command variables ($\phi_c, \theta_c, \dot{\psi}_c$). This part of the controller was designed with Dynamic Inversion. The task of the path tracking loops is to make the aircraft follow flight path and speed references. Four modes were designed: for the approach phase the Total Energy Control System (TECS) was used for decoupled tracking of flight path angle and speed commands, and a classical PD control law was used for lateral flight path tracking. Shortly before touchdown, the flare law, based on the so-called variable Tau principle, takes over in order to decrease vertical speed to an acceptable level for touchdown. The thrust is reduced simultaneously using a retard function. Laterally, a classical align mode takes over from the lateral path tracking mode in order to align the aircraft with the runway centre line in case of cross wind, while keeping lateral deviation to a minimum.

The task of the guidance loop is to derive flight path references from guidance signals for the path tracking loops. For autoland those are localiser (LOC) and glide slope (GS) radio signals. The LOC and GS structures are classical. In order to improve the estimation of metric deviations from the approach path, an altitude over threshold estimation was implemented.

In the Feedback Signal Synthesis block air data measurements are filtered complementary with inertial counter-parts in order to reduce the noise level due to turbulence. Also the side-slip angle is estimated for use in the inner loops.

The controller structure was implemented in Simulink. The dynamic inversion controller contains inverse model equations. These are automatically derived from the aircraft model in Dymola by swapping inputs and outputs and utilising Dymola's code generator. The advantage of dynamic inversion is that automatic gain scheduling and good nominal decoupled tracking performance is provided with little effort. A new methodology was used to deal with the robustness problem, involving optimising parameters in the inverse model equations.

4.7.2 Design Cycle

The design cycle for tuning the control laws is depicted in Figure 4-9. Inner, tracking, and guidance loops are designed sequentially or simultaneously. For each controller component an optimisation sub-task was defined. This involves modelling of the selected architecture (right) and selection of appropriate design criteria for tuning and compromising (left). Macros for computing criteria from nonlinear (e.g. simulations) as well as linear (e.g. eigenvalues) analysis were written. The criteria are scaled either using a factor or using so-called good-bad values, which allow for scaling 'goodness' of a computed criterion in a fuzzy-linguistic manner.

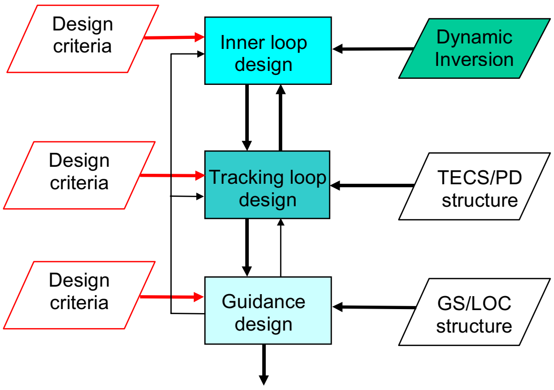

Figure 4-9: Interaction between design tasks

For tuning of the flare and glide slope modes the Monte-Carlo analysis software SIMPALE was incorporated into the optimisation, by developing an interface with the optimiser MOPS. Risk values were directly addressed as optimisation criteria. In this way an acceptable solution was found automatically, whereas otherwise fulfilling average risk requirements turned out to be difficult to achieve. The optimisation progress is depicted in Figure 4-10. Nominal performance is addressed via criteria from a single landing simulation, robust performance is addressed via Monte-Carlo analysis.

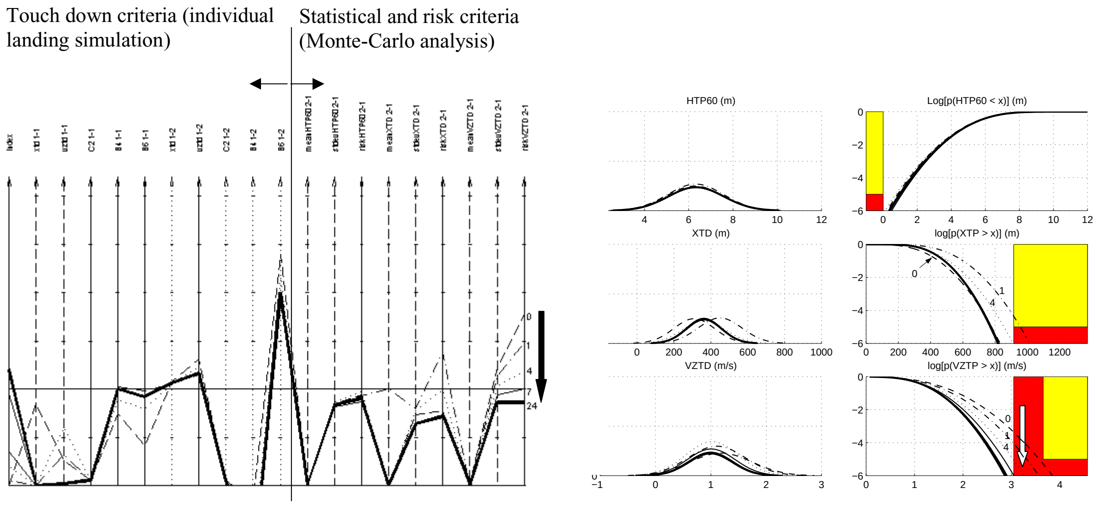

Figure 4-10: Optimisation of risk criteria obtained from SIMPALE Monte-Carlo analysis (arrows show fulfilling of risk value of touchdown speed).

4.7.3 Design Results

Based on extensive analysis using the RealCAM shell software and SIMPALE, it can be concluded that the DLR autoland controller meets practically all performance and robustness criteria defined in the benchmark definition. Figure 4-11 and Figure 4-12 illustrate nominal longitudinal and lateral touchdown performance.

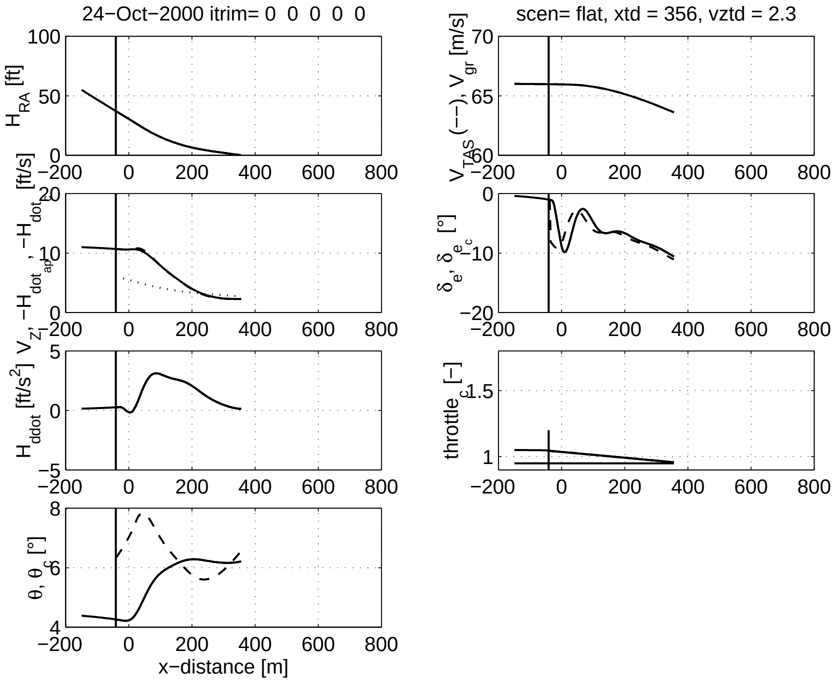

Figure 4-11: Flare time history of the nominal case

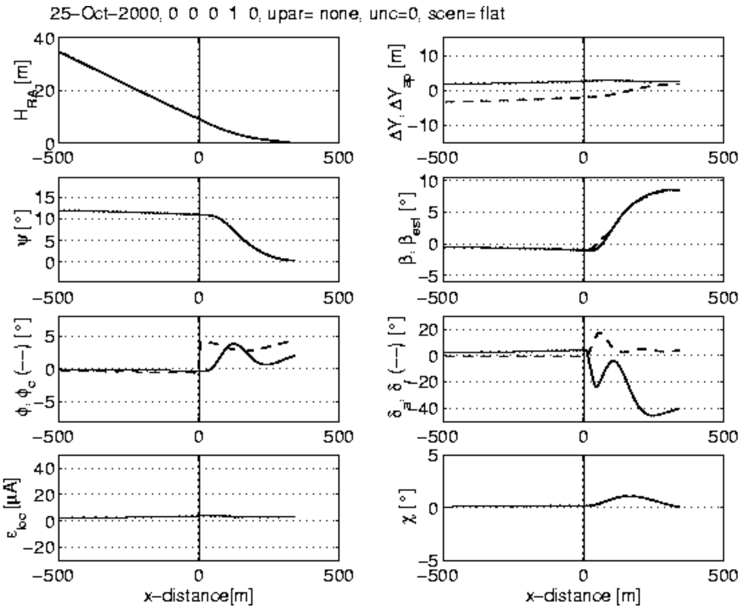

Figure 4-12: Lateral line-up time history for the nominal case with full crosswind

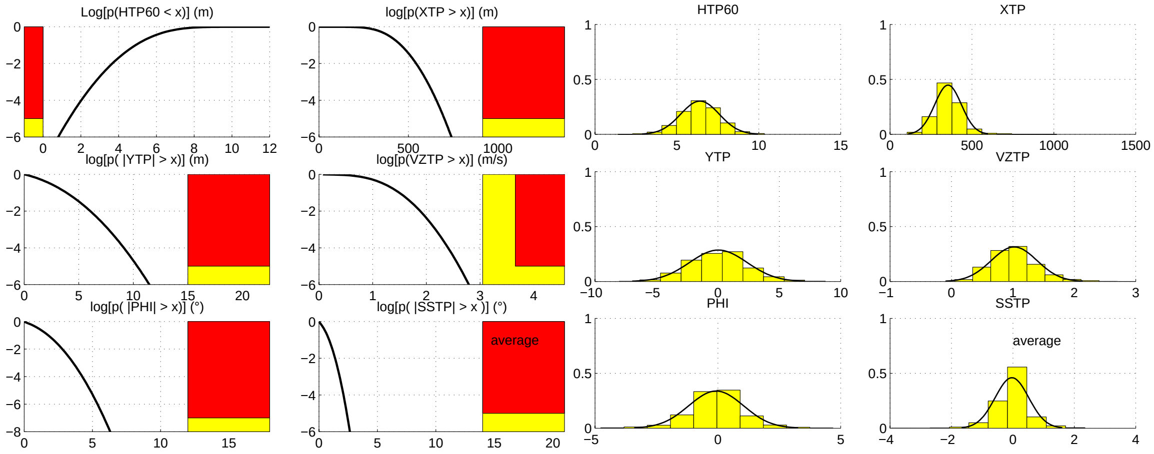

Figure 4-13: Average risk results from SIMPALE Monte-Carlo analysis.

Monte-Carlo average risk analysis is passed, even when aerodynamic model uncertainties are varied additionally. This proves robustness to aircraft configuration, airport and atmospheric parameter variations, as well as uncertainties to modelling errors. Limit risk criteria (calculated via an MC-analysis with one parameter fixed at its maximum or minimum value) are not presented in this report but were fulfilled as well, except for maximum headwind and maximum crosswind conditions. This is caused by the accompanying heavy turbulence. To pass these limit risk criteria as well, further refinement of the selected controller architecture will be necessary assuming that a solution exists.

The DLR design results were issued in combined Deliverable D3.2b/D4.1b, which consists of a report and the controller software. See Appendix A

4.8 Robustness Analysis of the RealCAM designs

4.8.1 Description of the Evaluation Procedure

In **industrial practise**, a controller is developed on a model. During the actual flight test, aircraft behaviour is always (slightly) different from the model due to parameter uncertainties and model simplifications. The designed controllers should be robust enough to cope with these differences.

In the **REAL project**, this situation is simulated by the fact that the design teams have received a *simplified* version of the aircraft model in SIMPA. Thus, the model for which the controllers have been designed is also different from the model which is used for evaluation.

Important remarks:

In fact, the procedure described above makes the SIMPA test in the REAL project quite severe. In the industrial design process, this would be equivalent to performing 2000 landings (a Monte-Carlo analysis) with actual flight tests, under environmental conditions which may vary up to the maximum allowed design limits. In industrial practice, the flight tests with the actual aircraft are only used to validate the models and the robustness analysis results of the Monte-Carlo tests.

The following steps were performed to assess the robustness of the DLR and ONERA controllers:

1. *Validation of the implementation in SIMPA*

   The objective of this task is to compare results from SIMPALE and SIMPA in order to check whether the controllers have been correctly implemented in SIMPA. The C-code of the ONERA and DLR controllers was correctly implemented in SIMPA. A few bugs were found and corrected. Model differences between SIMPA and SIMPALE still existed in the actuator delays, ground effect and engine response. It might be due to these model differences that the DLR controller in SIMPA showed a 3 second periodic mode on all actuators which did not exist during closed loop testing with SIMPALE.
2. *Deterministic analysis*

   This task checks the stability and performance robustness of the controller to a limited number of analytically defined disturbances (step inputs).
3. *Monte-Carlo analysis using SIMPA*

   This task evaluates the overall robustness of the controllers with respect to many realistic disturbances, taking into account their probability. 2000 landings are performed with randomly varying parameters. For each case it is evaluated whether the location of touchdown, vertical touch down speed, tire slip angle, lateral deviation from the runway centreline and bank angle are within the allowed limits.

Note: As mentioned above this is a very severe test in the REAL project set-up, since it is equivalent to performing a Monte-Carlo analysis in flight, i.e. performing 2000 landings with the actual aircraft. This is never done in industrial practise.

4. *Virtual flight tests*

   The Monte-Carlo analysis focuses mainly on the touchdown point. To assess the aircraft behaviour throughout the entire autoland, time histories should be evaluated as well. Therefore, virtual flight tests are performed. By replaying disturbances, which were measured in actual flight tests, it is possible to perform a detailed performance assessment of the controllers with realistic disturbances. This is the most interesting test.

The results of the SIMPA evaluation have been reported in combined Deliverable D4.2/D5.2 and were fed back to the design teams. They have incorporated assessment results into the design reports and commented on those results in an additional chapter. See Deliverable D3.2/D4.1 referred to in Appendix A. The next two sections also presents some results.

4.8.2 Robustness Assessment of the ONERA Controller

Deterministic validation results

The ONERA controller shows good stability and performance on the longitudinal axis in guidance, speed and pitch attitude control. The lateral guidance and bank angle control is acceptable for nominal aircraft mass but a bit “lazy” due to weak rudder and aileron control. The flare is acceptable and is sufficiently robust against wind and terrain profiles. The engine command is step-like, which is unrealistic, but this is filtered by the engine response.

Monte-Carlo analysis results

The vertical speed at touchdown is acceptable, and it is expected by AS that with minor modifications the requirements can be met. The touchdown distance control is bad, which is partly caused by the differences between the design model and the analysis model in ground effect, actuators and engine nonlinearities. The ONERA controller is not sufficiently robust against various wind conditions. In the lateral plane, the bank angle control and the lateral touchdown distance show a too wide scatter, mainly in high turbulence conditions.

Combined Deliverable D4.2/D5.2 reports the obtained numerical Monte-Carlo results. Due to the severity of the SIMPA test these quantitative results should be interpreted with caution, and are regarded as less interesting by industry.

Virtual flight test results

The results of the virtual flight tests are summarised in Table 4-1 below:

	Longitudinal	**Lateral**
Guidance	• Glide slope tracking a bit "lazy" • Acceptable flare, but long flare • Good speed tracking	• "Lazy" localiser tracking – Marginal guidance stability • Too loose heading control • Acceptable alignment with the runway at touchdown
Control	• Acceptable pitch control • Acceptable vertical speed control	• Bad bank angle control
Actuators	• Engine: high peak to peak values and too much high frequency activity • Elevator: medium peak to peak values, acceptable high frequency activity	• Aileron activity acceptable • Rudder: high peak to peak values, but acceptable high frequency activity

Table 4-1 Virtual Flight Test results of the ONERA controller

4.8.3 Robustness Assessment of the DLR Controller

Deterministic validation results

The DLR controller has good guidance performance on both the longitudinal and lateral axes, and good control of speed, pitch angle, bank angle and tire slip angle. The flare is initiated quite late but is acceptable. The engine command is step-like and not smooth, which is unrealistic, but this effect is filtered by the engine response. The rudder and aileron activity is reasonable, but on all lateral parameters a badly damped 3 second periodic mode is visible.

Monte-Carlo Analysis results

In the lateral plane, bank angle and tire slip control are good, which is confirmed by the virtual flight tests. The touchdown distance and vertical speed at touchdown show insufficient robustness which is partly caused by differences between the design model and the analysis model, as discussed before. Disturbance rejection in case of turbulence is not sufficient. The standard deviation for longitudinal and lateral landing distance is too high.

Again, the numerical results of the severe SIMPA Monte-Carlo test, as reported in combined Deliverable D4.2/D5.2, should be interpreted with caution, and are of less interest to industry.

Virtual flight test results

The results of the virtual flight tests are summarised in Table 4-2 below:

	Longitudinal	**Lateral**
Guidance	• Acceptable glide slope tracking • Late flare, then over flare • Good speed tracking	• Good localiser tracking • Very good heading control • Very good alignment with the runway at touchdown
Control	• Good pitch control • Good vertical speed control	• Good bank angle control
Actuators	• Engine: weak low frequency activity but too much high frequency activity • Elevator deflections ok, but too much high frequency activity	• Aileron activity acceptable • Rudder deflections ok, but too much high frequency activity

Table 4-2 Virtual Flight Test results of the DLR controller

4.8.4 Conclusions of the SIMPA Robustness Evaluation

When interpreting the evaluation results, the severity of the SIMPA test and the limited time available for the actual design should be taken into account. In normal industrial practise, the final Monte-Carlo test is performed on the same model that is used for design. Within REAL, model differences were deliberately introduced to simulate industrial practise where differences between model and the actual aircraft exist.

In general, the longitudinal behaviour of the ONERA controller was satisfactory and there is not much difference between the design environment SIMPALE and the evaluation environment SIMPA. However, the lateral behaviour is quite different in SIMPA. The exact cause could not be determined and therefore may have contributed to the SIMPA evaluation outcome.

The performance of the DLR controller is satisfactory. The designed control laws seem to be sensitive to unmodelled delays and nonlinearities. The high activity on the actuators might be caused by these unmodelled dynamics. Pilots do not feel comfortable with very active (nervous) actuators, thus the robustness for unmodelled effects should be increased.

During the evaluation both controllers do show robustness with respect to the specified parameter uncertainties and parameter variations. However the robustness with respect to unforeseen uncertainties is not sufficiently proven. Unforeseen uncertainties, for instance due to model differences, have to be dealt with daily in industrial practise. The goal of achieving a “first time good enough” controller is not met from a robustness point of view. It is recognised however, that the design methods are straightforward and powerful. The short design cycles and the easy inclusion of new design objectives are appreciated by industry.

The industrial evaluation was reported in combined Deliverable D4.2/D5.2, see Appendix A.

5 RealATTAS Activities

5.1 Objectives

The objectives of the RealATTAS activities were:

- To demonstrate the efficiency of the design process developed during the RealCAM activities, by designing a controller for a different aircraft within a timeframe half as long as for the RealCAM designs,
- To demonstrate that the resulting controllers from the design process can be easily implemented in an actual aircraft and pass a flight test.

5.2 RealATTAS Benchmark Definition

The RealATTAS benchmark definition is structured in a similar manner as for RealCAM. Only the open-loop analysis has been shifted to the predesign activity. The contents of the benchmark document are the same, except for the aircraft specific parts. Below, only the differences with the RealCAM benchmark document are given.

The mission to be flown is the same as for the RealCAM benchmark, only the values in some aircraft specific design requirements have been adjusted to ATTAS. The ATTAS aircraft of DLR is based on a VFW 614 civil transport aircraft, which was modified to serve as a flying simulator and demonstrator.

Firstly the existing nonlinear aerodynamic model of DLR’s ATTAS aircraft has been simplified. These ATTAS aerodynamics have been implemented in the software tool Dymola in which the full RealATTAS model was developed. From Dymola, simulation code for use in Matlab/Simulink was automatically generated.

For evaluation of the RealATTAS designs a new version of SIMPALE has been developed by ONERA (referred to as SIMPALE 2). In this version the RealATTAS model has been integrated. The other closed-loop analysis tools from the RealCAM benchmark could be reused.

Finally, a design shell, similar to the RealCAM design shell has been developed, in which all software (model, evaluation tools and SIMPALE 2) has been integrated.

The results of the RealATTAS benchmark work (Deliverable D1.2) are report TP-04 and a software shell, the so-called RealATTASShell, see Appendix A.

5.3 RealATTAS autoland predesign

Just as for RealCAM, the objective of the predesign was primarily to test and debug the benchmark model and software, not to design a perfect controller. However, the predesign could also have been used by the design teams to identify which robustness aspects of the design were found complex and difficult to cope with. Again, like in the RealCAM activities, the controller software developed by NLR and DUT could not be directly used by DLR and ONERA.

The design of the longitudinal autoland modes (glide slope and flare modes) was performed by DUT. The design of the lateral modes (localiser and align/decrab modes) and the integration of longitudinal and lateral controller were performed by NLR.

For the RealATTAS predesign the RealCAM predesign controller was taken as a basis. The same design techniques were applied, i.e. conventional methods for longitudinal and lateral inner loop and for localiser tracking, TECS for longitudinal glide slope tracking, and the variable Tau method for flare control.

The predesign controller proved to be robust with respect to variations in mass and centre-of-gravity location. The robustness against wind shear and external disturbances (ILS noise, turbulence) is not satisfactory and unacceptable landings occur. Not all the performance requirements are met, but some were not taken into account for the predesign.

The predesign work was reported in TP-07. Also controller software is available, see Deliverable D3.3 in Appendix A.

5.4 RealATTAS Autoland Design I: ONERA

The design process and the controller structure as defined in Section 4.4 were applied to RealATTAS in a very similar way. The differences concern the details listed below.

Concerning steps **2** to **4** of section 4.4:

- The initial inner law was initialised taking into account the open-loop dynamics of the aircraft (choice of eigenvalues) which are obviously different considering both aircraft.
- The interpolation formulae used for obtaining scheduled gains were simplified: In the lateral case scheduling is not needed, in the longitudinal case, interpolation becomes straightforward as it is not necessary to consider interpolation during the design step.

Note that used tracking laws are the same for both aircraft, in addition, it was not necessary to develop new code for analysis and design.

The main differences are related to steps **1** and **5** of the design process. For example:

- Complementary filters for evaluation of the derivative of the lateral deviation were added.
- The engine of RealATTAS possesses a backlash requiring a specific treatment. This treatment consisted of an additional loop in the output signal-processing block (see Figure 4-2) in order to speed up the engine response in some conditions.

The fact that RealATTAS measurements are quantised obliged ONERA to remove the processing block taking into account the terrain slope before threshold and the runway slope.

The results concerning RealATTAS are very close to those obtained with RealCAM. A comparison of Figure 4-3 and Figure 5-1 shows similar time responses. A comparison of Figure 4-4 and Figure 5-2 shows similar results concerning internal dynamics. So the conclusions of section 4.5 related to the robustness of the RealCAM inner law are the same for the RealATTAS design.

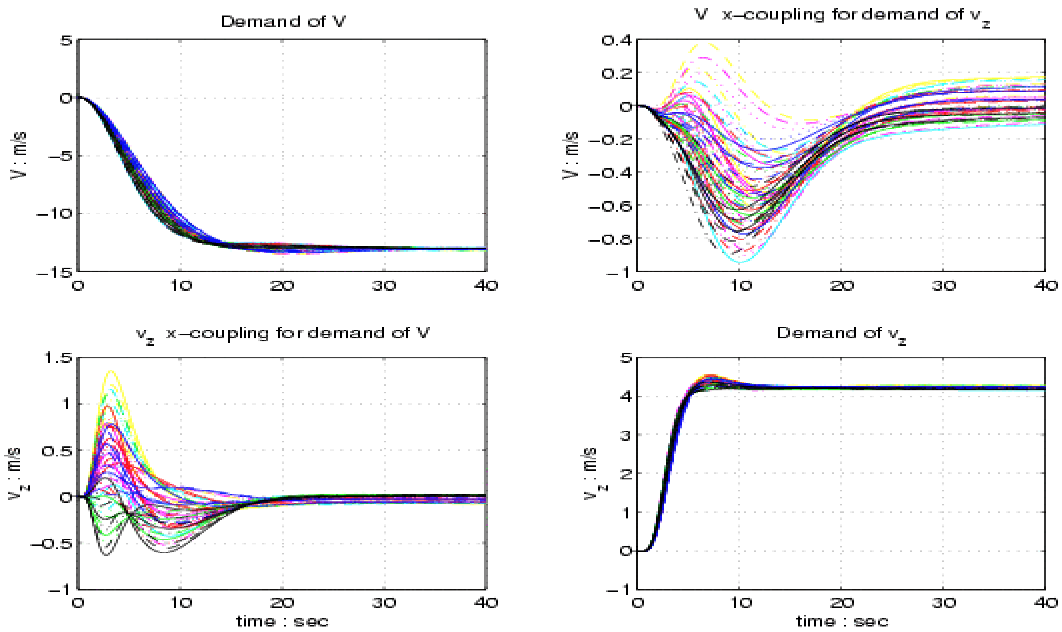

Figure 5-1 RealATTAS - Longitudinal inner loop assessment (time response)

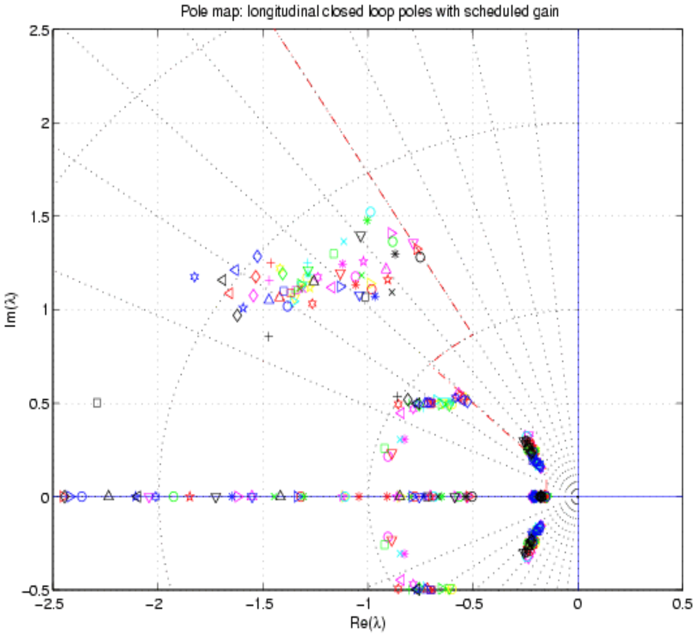

Figure 5-2 RealATTAS - Longitudinal inner loop assessment (pole map)

Concerning the global robustness properties of the autopilot, the results obtained for RealATTAS are very similar to those obtained for RealCAM. A comparison of Figure 4-5 and Figure 5-3 shows slightly better results in the RealATTAS case, except for the vertical speed at touch down (VZTP) that has been deteriorated.

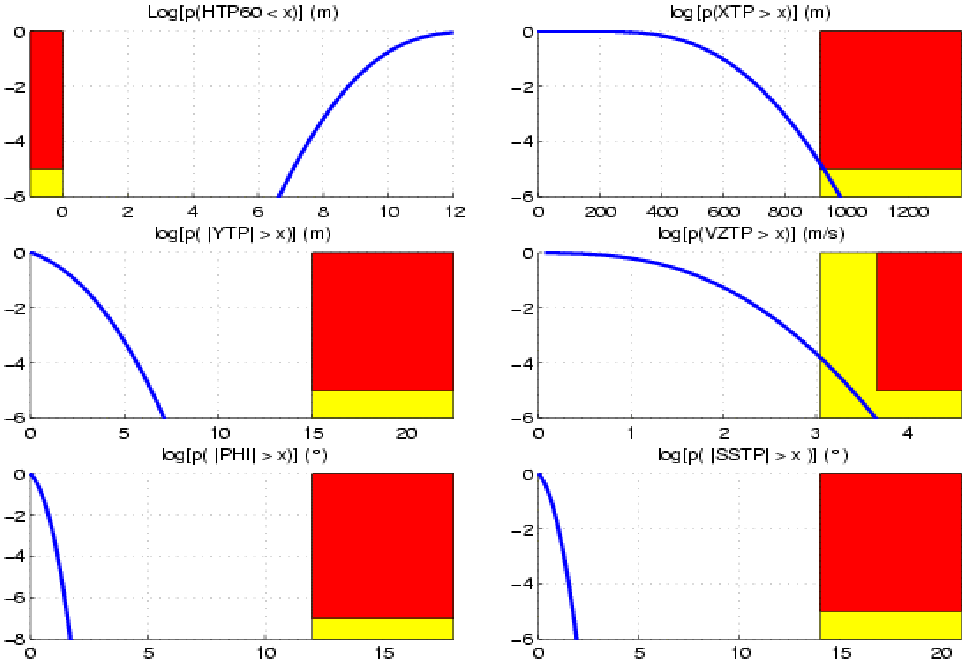

Figure 5-3 RealATTAS - Aerodynamical and inertial uncertainties (SIMPALE 2 cumulative distributions)

ONERA's RealATTAS design results have been reported in combined Deliverable D3.4a/D5.1a, see Appendix A.

5.5 RealATTAS Autoland Design II: DLR

5.5.1 Controller Architecture

For RealATTAS, the same design procedure was used as for RealCAM (section 4.6). The general controller architecture (Figure 4-8) was kept the same. The dynamic inversion control laws were newly generated from the RealATTAS model in Dymola. The inverse thrust map and the side-slip estimation had to be adapted to RealATTAS as well. During ground-based simulator testing, minor additional modifications turned out to be necessary to cope with effects such as quantised signals, aircraft asymmetry, and considerable backlash in the engine response.

5.5.2 Design Cycle

The controller was tuned according to the same design cycle as depicted in Figure 4-9, using the same optimisation set-ups as for RealCAM. For the longitudinal design glide slope, tracking and inner loops were optimised simultaneously. This was done by simply augmenting the corresponding optimisation sub-tasks, see Figure 5-4.

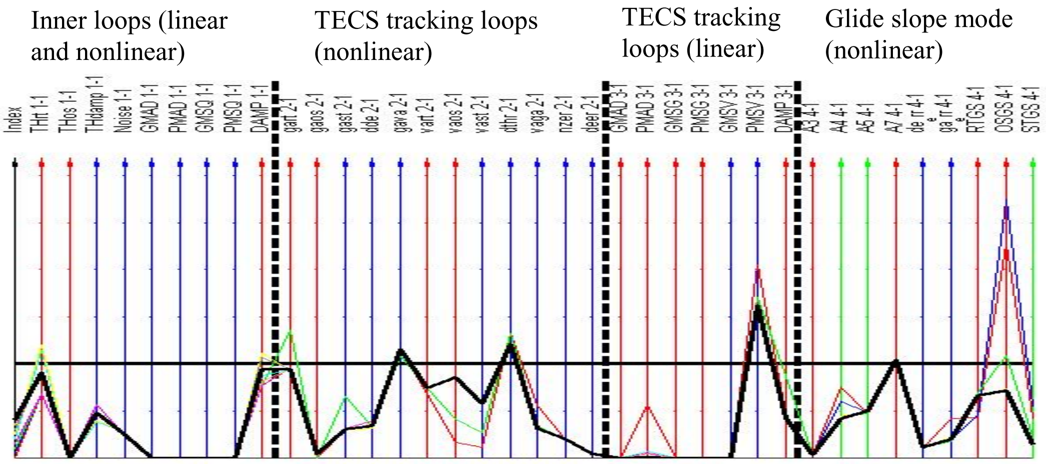

Figure 5-4: Simultaneous optimisation of longitudinal loops: scaled design criteria in parallel co-ordinates (linear/nonlinear refers to criteria computation).

5.5.3 Design Results

The RealATTAS design meets the design requirements and was successfully flight tested in ATTAS. Monte-Carlo results show that the average risks were met (see Figure 5-6).

It has been demonstrated that the proposed design process can be efficiently applied to a different aircraft. A good autoland controller was developed in a short time (~ two months, including benchmark updates; on average, two designers involved). The controller could be implemented in the real-time flight control computer and was successfully flight tested.

DLR's RealATTAS design results have been reported in combined Deliverable D3.4b/D5.1b, see Appendix A.

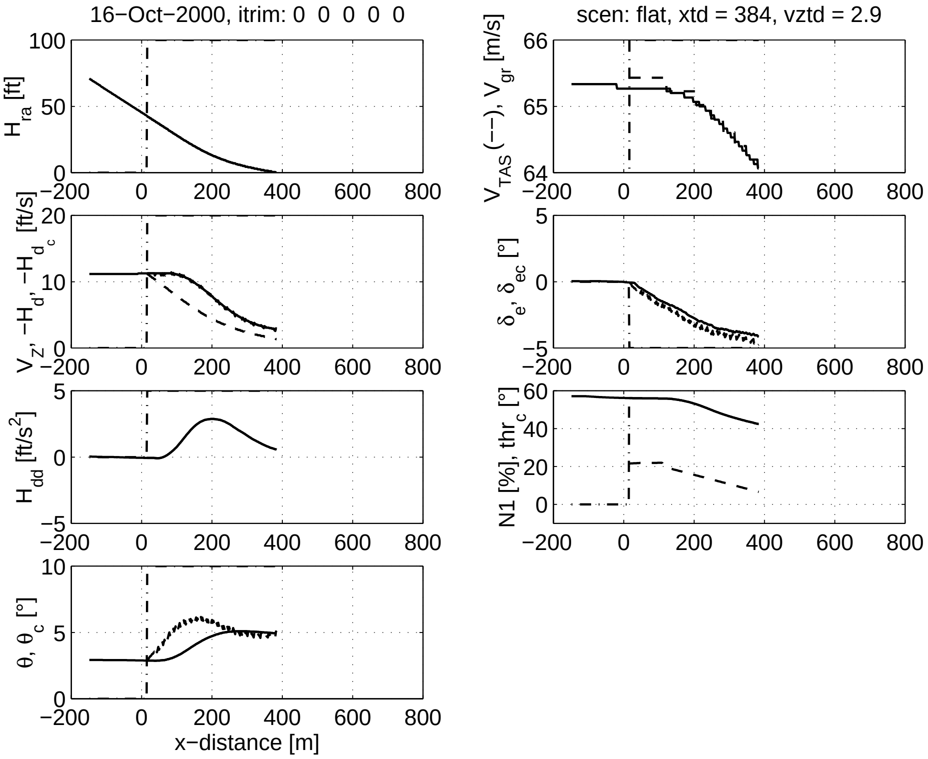

Figure 5-5: Nominal flare for flat terrain and no wind.

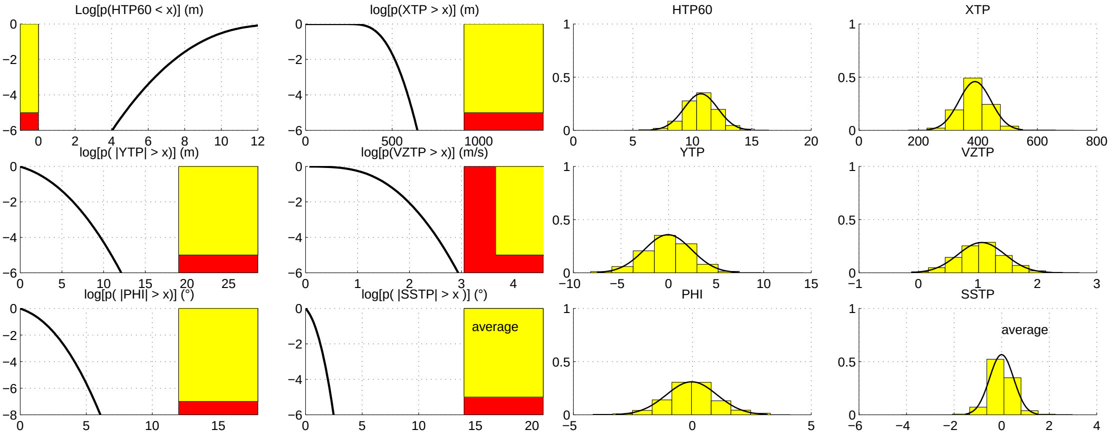

Figure 5-6: Average risk results from SIMPALE Monte-Carlo analysis.

5.6 Flight Test Results

The robustness of the controllers was assessed with SIMPALE 2. After the RealATTAS controllers were delivered to DLR the following procedure was followed:

First the controllers were implemented and tested in the ground based simulator at DLR. If the implementation was successful and pilots had good confidence in the controller performance in the simulator, the controllers could be implemented in the actual aircraft's flight computer. A photo of the aircraft is presented by Figure 5-7.

The flight test crew consists of two test pilots: the evaluation pilot and the safety pilot. As soon as the controller induced unsatisfactory motion of the aircraft, the safety pilot could disengage the autopilot.

The test pilots gained confidence in the controllers by performing landings on virtual runways at 500 ft, 300 ft and 100 ft altitude respectively. After the landings on the virtual runway were successful, the team would perform actual landings. Three slots were available for the flight tests in the period July-September 2000.

Figure 5-7 DLR's Flying Testbed "ATTAS"

5.6.1 DLR controller

The DLR controller was tested in the ground based simulator at DLR-BS. Then the DLR controller was successfully tested on the virtual runways on 500 ft, 300 ft and 100 ft. During the second slot, three successful autolands were performed with the DLR controller at Cochstedt Airport. The touchdown distance was calculated. The touchdown distance may vary between 250 m and 600 m after the threshold. The measured distances (with an accuracy of ±10 m) were: 488 m, 352 m and 481 m respectively. All landings were thus within the allowed touchdown zone. A flight test result of the longitudinal behaviour of the ATTAS aircraft during the flare is given in Figure 5-8. The lateral result is presented in Figure 5-9. Controller deflections and wind information are depicted in Figure 5-10. A few seconds after touchdown, the crew reverted from autoland control to manual control because no roll–out guidance was developed in this project. The moment this occurred is indicated by parameter flcon as it switches from 1 to 0.

5.6.2 ONERA controller

The ONERA controller was also first tested in the ground based simulator. Based on the results of these first tests, the interface between the controller and the environment was modified. During the flight tests of the ONERA controller in the second slot, some external problems occurred during the approaches on the 500ft and 300ft virtual runways at Cochstedt airport. These problems were not caused by the controller but due to the coupling of terrain profile and virtual ILS signal computation algorithm. These tests had to be redone at Hannover Airport at the beginning of the third slot. Finally the controller was tested at Cochstedt airport, where the 100 ft virtual runway test was passed. Then, two actual landings were attempted. The ONERA controller did not touch down, but flew parallel to the runway at 2 ft altitude. This behaviour did not occur during the design and ground based simulation. It is caused by the fact that the throttle is not completely reduced to idle. Due to the higher kinetic energy level, the aircraft is more sensitive to differences between the actual ground effect and the modelled ground effect. The ONERA controller was redesigned very efficiently and tested successfully in the design environment. No time and budget was left in the project to test the updated controller in the ground based simulator and in flight. It is expected by the design team that the ONERA controller will now perform satisfactory during actual landing.

5.6.3 Conclusions from the flight test

In the flight test phase it was demonstrated that both design processes are capable of producing, within a short time span, realistic controllers which can be implemented straightforward into ground based simulators and real flight control computers. This shows the efficiency of the processes to perform designs on different aircraft types.

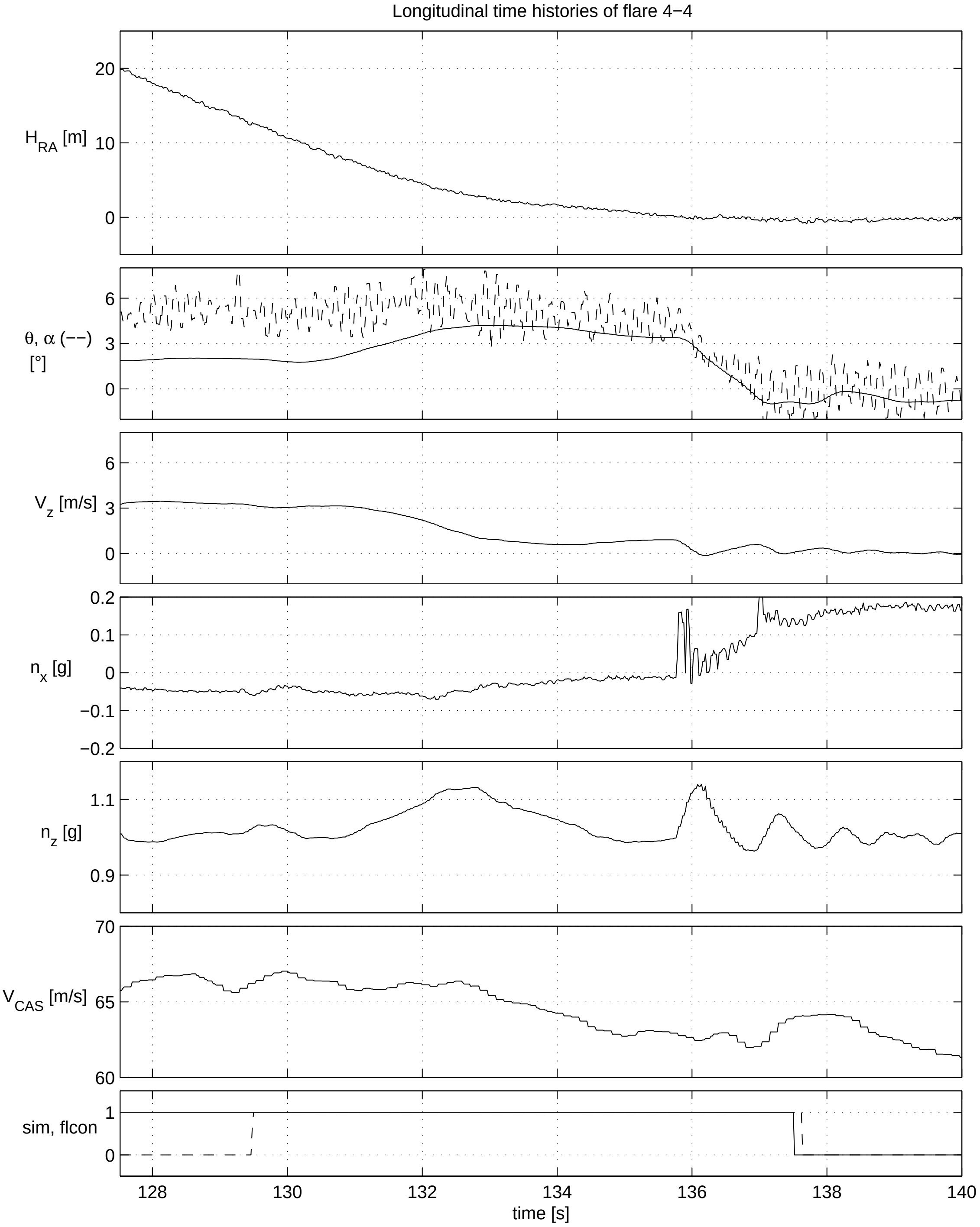

Figure 5-8 Longitudinal time histories of the flare of flight test 4-4 of the DLR controller

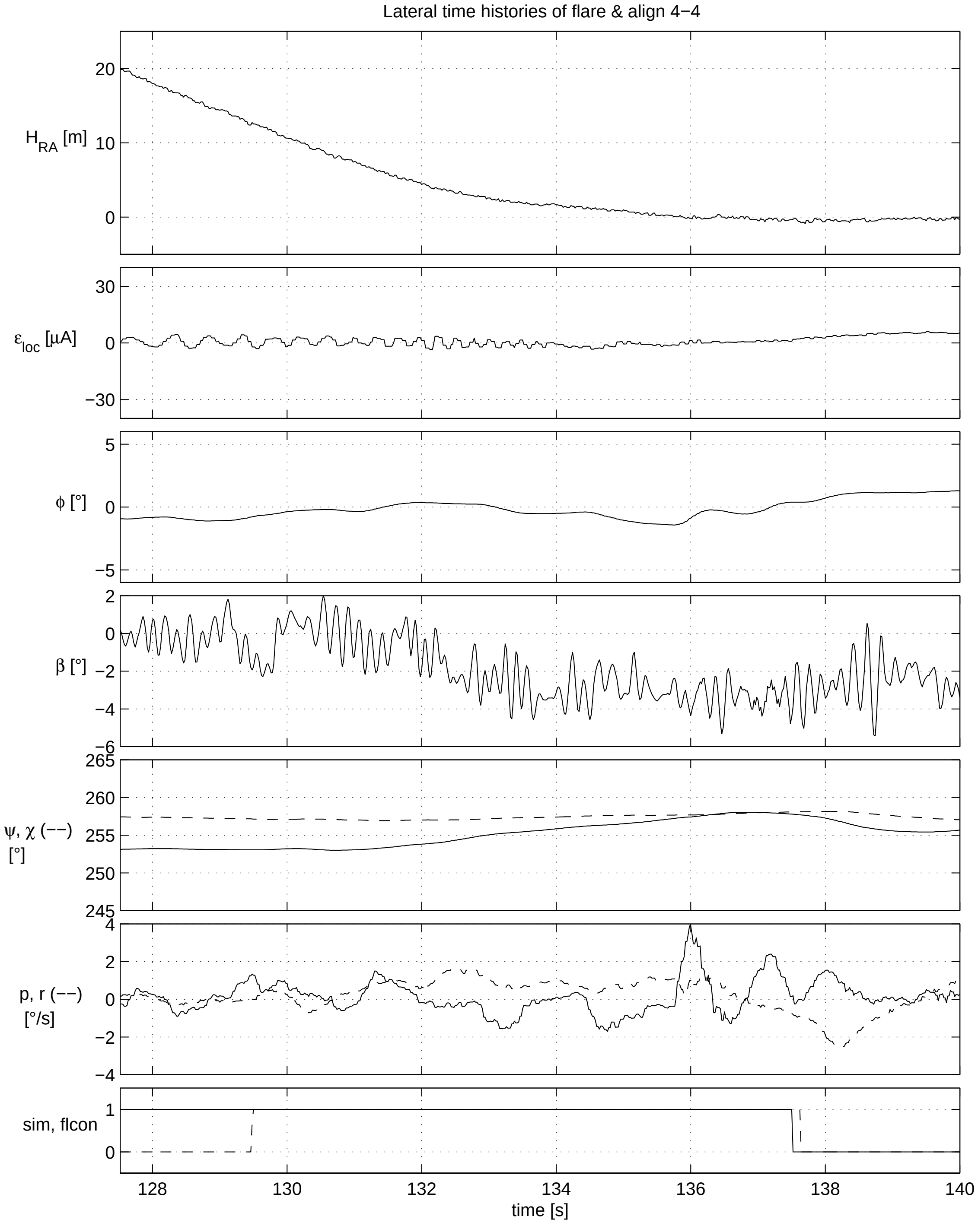

Figure 5-9 Lateral time histories of the flare and align; flight test 4-4 of the DLR controller

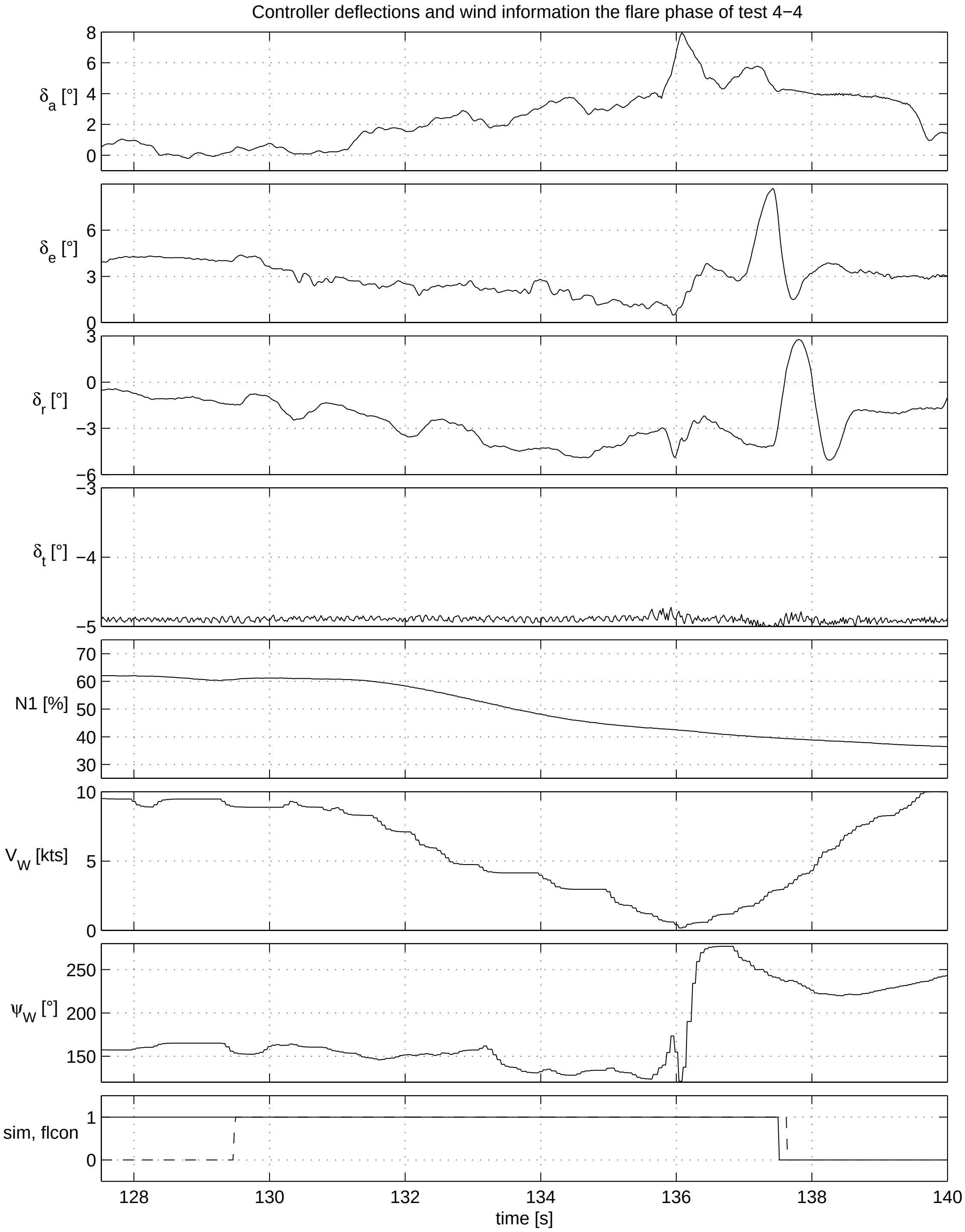

Figure 5-10 Control deflections and wind information during the flare of flight test 4-4 of the DLR controller

6 Industrial Evaluation

In the previous sections it was described how each of two design teams has each developed a design process based on modern control law design methods. During the economical benefits study (chapter 3), nine criteria have been developed to assess the efficiency and applicability of the two design processes. These criteria have been issued in a separate Technical Note TN-02 and have been incorporated into the benchmark problem definitions for RealCAM and RealATTAS. Table 6-1 gives a brief overview of the evaluation of these criteria. The objective of this table which contains only limited information is not to compare the DLR and ONERA approach, but to identify for each approach its strengths and weaknesses.

#	**Short description**	**DLR**	**ONERA**
1	Good enough controllers after off-line design (pass SIMPA test and Flight Test)	√ for performance X for robustness √ for efficiency	√ for performance X for robustness √ partially for efficiency
2	Uncertainties taken into account explicitly in design method	√ yes (significant computing power required)	√ partially, all uncertainties taken into account but some could be taken into account earlier
3	Automation of the process where possible	√ all suitable aspects automated	√ partially, currently automation not better than current industrial practise, but further automation possible
4	Process suitable for inclusion of additional requirements after the off-line design phase	√	√
5	Indication of level of understanding required for application of the process - level of understanding required - How steep is learning curve - How easy is redesign for ATTAS	 Moderate Easy Very easy	 Low/Moderate Moderate Moderate/difficult
6	Process applicable to different aircraft types	√ ATTAS design completed in short time	√ ATTAS design completed in short time
7	Process applicable on different controller structures	√ process independent of controller structure	√ for linear control X for nonlinear controller structures

#	**Short description**	**DLR**	**ONERA**
8	Transparency of the resulting controllers	√ except for DI block	√ understanding quite simple
9	Resulting controllers can be implemented in actual flight control computers	√ as shown by ATTAS Flight test	√ as shown by ATTAS Flight test

Table 6-1 Process Evaluation Summary
(√ = criterion fulfilled, X = deficiencies, for details see [5])

Concerning Criterion 5, it should be noted that the theory of Eigenstructure Assignment itself is easy to learn by newcomers. However, it is less transparent how design requirements should be translated into a format which is suitable for the method. Therefore the rating "low/moderate" was given by industry.

In the REAL project, a lot of aspects have been found that have the potential to improve current autopilot design processes. Taking the limited budget of the REAL project into account, and considering the amount of modelling work that had to be done as pre-requisite, very substantial and very satisfactory results have been obtained for a low budget.

The most interesting aspects of the proposed design procedures are:
- to consider multiple design objectives simultaneously by multi-objective optimisation,
- to develop and demonstrate a 'light' edition of the Monte-Carlo simulation tool (SIMPALE) which can be integrated into an optimisation process within reasonable computing time requirements,
- to address robustness by a multi-model approach and worst-case search,
- to consider Eigenstructure Assignment for the linear design of inner loops.

All of those aspects seem to be mature and are ready for implementation into the industrial design process in order to improve the efficiency and to design more robust controllers.

Further research on the following aspects is strongly encouraged.
- Dynamic Inversion (DI):
  Automatic definition of controller structures by DI is of high interest. But the impact on the industrial DPs is not fully understood yet. This requires further basic research. A well-suited (flight control) design task should be defined.

- Eigenstructure Assignment (EA):
  EA is very powerful for linear design tasks and when all design requirements can be translated directly into the method-dependent language. In flight control problems, design

requirements often exist that cannot be translated directly into this format. Here, a combination of EA and optimisation techniques seems to be promising. Furthermore, deeper and better-documented knowledge on how to translate different types of criteria into a method-dependent language would be very useful.

7 Project Synthesis, Conclusions and Recommendations

In the previous sections, the technical achievements have been described. In the present section the results are synthesised, and the conclusions and recommendations are listed.

7.1 Synthesis of results

The current industrial autopilot design processes use a highly iterative approach to design control laws that are sufficiently robust to modelling errors, parameter uncertainties and varying environmental conditions. These design iterations are costly, especially when required in the advanced simulator and flight test phases of the design process. In the REAL project two design processes including different robust design techniques were investigated from which it was expected that these could provide more mature and robust controllers than conventional techniques at an early stage in the design process.

First a challenging autoland design problem was set up by the partners to address the industrial design task. Two simplified, but still realistic design processes were defined. Separate design teams were set up, one from ONERA and one from DLR. Each design team applied a different design process with a different robust design method. ONERA applied the “Multi-model Eigenstructure Assignment” method and DLR a “Multi-model, Multi-objective Optimisation” method combined with the Dynamic Inversion technique. The two individual design teams successfully applied their design method and associated design process to two different aircraft models, as described next.

The first model for which robust controllers have been designed was a large passenger aircraft of about 123 to 180 tonnes. This so-called RealCAM model, i.e. Real Civil Aircraft Model, was a simplified version of the extensive aircraft model used inside AS’s sophisticated autopilot evaluation environment SIMPA. Also a simplified edition of SIMPA’s Monte-Carlo tool (called SIMPALE) has been developed by ONERA for implicit use in the RealCAMShell, being the controller design environment. The RealCAMShell environment was tested by a predesign jointly executed by DUT and NLR. During the design period autoland controllers were developed and tested on robustness using SIMPALE. The SIMPALE results obtained proved that the two RealCAM controllers were quite robust against the model-specified uncertainties and the various aircraft operating conditions. The resulting autoland controllers were delivered to industry. The integration into the industrial’s assessment environment was made possible using specially developed interfaces and automatic code generation. The robustness properties were reassessed, both qualitatively and quantitatively, using SIMPA. The qualitative assessment consisted of an analysis of aircraft (plus controller) responses on deterministic inputs and also of virtual flight tests made of automatic landings with real life recorded (atmospherical) input data. The quantitative assessment was performed via a Monte-

Carlo analysis using the more comprehensive aircraft model. The qualitative results indicated both autoland controllers had some weak and some strong points, essentially implying that both controllers should be improved on certain aspects. In general, the longitudinal behaviour of the ONERA controller is satisfactory. However, the lateral behaviour was quite different in SIMPA (when compared to SIMPALE). The exact cause could not be determined and therefore may have contributed to the quantitative evaluation outcome. The lateral and longitudinal performance of the DLR controller is satisfactory, although the flare initiation was sometimes a bit late. The control laws seem to be sensitive to unmodelled delays and nonlinearities since high activity on the actuators was present. Pilots do not feel comfortable with very active (nervous) actuators thus the robustness for these unmodelled effects should be increased.

Both controllers appeared not sufficiently robust to pass all Monte-Carlo requirements of SIMPA. This latter result was mainly found to be due to aforementioned non-specified differences in dynamic model aspects between RealCAM and SIMPA and not due to a defect of the design methods applied.

It would have been interesting to see how well both design methods would be able to cope with more stringent requirements on controller activity and with revised models in a second design cycle, but this was not further explored within the project. Yet model differences, for instance between various subsequent aircraft model versions or differences arising as a result of comparing models with the real aircraft, are a common part of industrial practice.

Based on the previous results, the very ambitious project’s aim of “first-time-good-enough” was, strictly spoken, not met when addressing overall robustness aspects. However, the modular and structured set up used within the project allows for an easy inclusion of updated or fully new models and refined design requirements. Also a fast redesign is possible to incorporate these new model aspects or new requirements into the robust controller design. Furthermore, industry emphasised that a kind of “one-shot-design” should be considered a utopia. It is not realistic to expect that all uncertainties or unmodelled real-world effects can be covered by a robust design in one single design cycle. That’s why the proposed design processes still contain iterative procedures. Seen in that context, the project goal has been over-ambitious. However, the design methods and tools applied, as well as the controller results, show that nowadays robustness can be addressed in a systematic manner, which provides the engineer with much insight into the problem and helps in dealing with the many design parameters and specifications simultaneously.

To investigate the efficiency aspects in more detail, both teams designed a second autoland controller on a simplified model of DLR’s ATTAS flying test bed. Reapplying their design process and making use of the same robust design method as used before, both teams succeeded in delivering new autoland controllers within a very limited allowed time span. Firstly, the controller design environment developed had to be adapted to include the specifics of the new model. Unfortunately, the set up of one part of this so-called RealATTASShell environment was not properly planned under the project. The tool SIMPALE-2, a SIMPALE version dedicated to this new aircraft model, was not ready in time in order to be applied by the design teams during their design (optimisation) process. It was used for a controller end-test on robustness instead. This revealed acceptable robustness properties and allowed both the controllers to be delivered to DLR, who integrated them in their ground-based simulator. Minor additional design modifications turned out to be necessary to cope with effects such as sensor biases, quantised signals, aircraft asymmetry, and considerable backlash in the engine response. This illustrates that the realisation of a ‘one-shot design-approach’ seems very unlikely.

Realistic flight hardware, like the real time flight computer was used during the ground tests. The software-to-hardware integration was greatly facilitated by the automatic code generation option that is available within the controller design shells. After the integration tests and piloted validation on the ground-based simulator, the controllers were easily implemented in DLR’s ATTAS aircraft. During a flight test phase in the summer/autumn 2000 period, successful autolands have been performed with the DLR controller. The controller developed by ONERA was also flight-tested. This latter controller let the ATTAS aircraft descent to within an altitude of 2 feet above the runway but the aircraft did not touch down. After identification of the reasons for this behaviour, the ONERA design team quickly and efficiently performed a redesign. Due to lack of time and budget the revised controller was tested again in the design environment only. Nonetheless, it is expected that also satisfactory results will be obtained in actual flight tests of automatic landings. Thus both teams have demonstrated that with the design methods used, and with the tools and processes developed, realistic autoland controllers can be designed, quickly implemented and validated in a ground test facility, and flown on a real aircraft, within the short time frame imposed. Both design methods have definitely proven to be useful to solve real life aeronautical engineering problems, and thus can be transferred to industrial practice. All this is considered as a very positive and convincing indication of the potential both robust design processes may have to address robustness issues and to improve the efficiency of the current industrial design processes.

A critical note should be placed on the time planned and actually used for all model (software) developments within the project. The complexity and the time-consuming aspects involved were clearly underestimated and this impacted the actual design work in budget and remaining time, and thereby in quality. Also the phasing and efficiency of the two predesign tasks was found to correlate not too well with the main design tasks. Nonetheless, within the limited time, budget and resources available for the project, good value was obtained for the available amount of money.

The industrial partners have evaluated the efficiency of the executed design processes. Strictly spoken, efficiency improvements could not be quantified or proven, since there was no conventional process available for direct comparison purposes. However, industry recognised that the used design processes and design methods are very powerful because the working of both methods was demonstrated on two different aircraft types by two teams who had not performed autoland controller design before. And even in the case of any unexpected model differences, which will always occur in real life, the overall automated set up developed and used in the project will speed up (re-)design activities considerably when compared to conventional design approaches.

It could not be demonstrated explicitly within the scope of the REAL project, but it is still expected that the investigated robust design techniques together with the developed automated set up can reduce the number of required iterations in the advanced stages of the design cycle, or at least can shorten the cycles themselves.

Finally, all partners agreed that sufficient evidence was given to state that the intentions behind the project's ambitious overall goal had been achieved.

7.2 Main Conclusions

The reader should consult the appropriate deliverables, referred to under Appendix A, for detailed conclusions on particular project aspects. However, based on the previous results described, and limitations set within the project, the following main conclusions are drawn:

- very substantial and very satisfactory results have been obtained for a modest budget, considering the amount of modelling work that had to be done as a pre-requisite.

- the project's aim of "first-time-good enough" was over-ambitious, strictly-spoken not met, but the intentions behind this objective were achieved since a kind of 'one-shot-design' is considered a utopia.

- when defining design specifications for autoland systems, real life hardware effects (e.g. sensor biases, quantised signals, etc) should be incorporated.

- both robust design methods have proven to be very powerful in designing realistic robust controllers for an autoland system of a civil aircraft.

- the applied robust design methods could address the specified robustness very well.

- the required time for software modelling and validation was severely underestimated and impacted the project’s robust controller design tasks qualitatively.

- the industrial assessment revealed that when applying robust design methods even unspecified model differences should be incorporated to the maximum extent possible.

- since the proposed design processes do not adhere to a specific controller structure, they create the maximum flexibility desired. It was clearly demonstrated that the processes could be efficiently applied to various aircraft.

- the two design processes were simplified versions of real life processes, but were found sufficiently realistic to perform a qualitative study on potential process efficiency improvements.

- in order to improve the efficiency and to design more-robust autoland controllers all of the aspects indicated below seem to be mature and are ready for implementation into the industrial design process:
    - to consider multiple design objectives and requirements simultaneously by multi-objective optimisation,
    - to develop and demonstrate a ‘light’ edition of the Monte-Carlo simulation tool (SIMPALE) which can be integrated into a design optimisation process within reasonable computing time requirements,
    - to address robustness by a multi-model approach and worst-case search,
    - to consider Robust Eigenstructure Assignment for the linear design of inner loops.

- the controller structures were set up via block diagrams under Matlab/Simulink that has the possibility to export the controllers in software code via automatic code generation (when using the Real-Time Workshop Toolbox). This has greatly facilitated the transfer of these autoland logics into the industrial assessment environment and into software used by real flight hardware.

- the REAL project has shown that the CEC framework is an excellent way to bridge the gap between research, university and industry by transfer of knowledge.

7.3 Recommendations

The reader should consult the appropriate deliverables, referred to under Appendix A, for detailed recommendations on particular project aspects.

However, for the project as a whole, the following recommendations are made:

- Much effort has been spent in defining, creating and validating all the benchmark software, i.e. with respect to the RealCAMShell and the RealATTASShell, which has now reached a mature state. The same is true for both the SIMPALE versions (i.e. SIMPALE and SIMPALE-2) and the MOPS/SIMPALE interface. Those tools should be re-used when possible, in order to minimise model development phases in any future, subject-related project.

- An interesting aspect is the automatic generation of an inverse model by Dymola for the Dynamic Inversion part of the autoland controller. However, this technique requires further basic research. A well-suited design task should be defined and further research on this topic is strongly encouraged.

- The technique of robust eigenstructure assignment should be investigated further, especially in combination with optimisation techniques and automation aspects. Special attention should be paid on the translation of design criteria into a format, which can be used in this method.

- In the REAL project, different teams performed the predesign and the actual design. Also different methodologies were used. In an efficient industrial environment, the predesign is an integral part of the design process so that experience and tools developed in the predesign can be (re-)used in the actual design. In any follow-on project the pre-design and design should preferably be performed by the same team, or transferable design methodologies should be considered already in the definition phase of the project.

- Given the fact that the autoland controllers did not meet all design criteria, and that they where not set up to perform an ILS intercept or roll-out guidance after touchdown, improvement and enrichment of the current controller structures should be investigated.

- Both design teams proclaim their applied robust design method to be very simple in its use, even by non-experienced people. It would be interesting to see to what extent the design processes and the tools are of help to an experienced designer from industry. This could be done in the frame of a follow-on project, in which tools can be customised to the partners. It is expected that hands-on experience with the design tools will be most beneficial for industry. Therefore an integrated team of research institutes and industry is recommended for an efficient knowledge transfer.

8 Exploitation and dissemination of results

This section provides a global view on the way the results obtained within the REAL project can be exploited and disseminated by the various partners. From the start of the project all partners favoured to use the results to support their individual exploitation activities.

8.1 Exploitation of individual partners

NLR

The knowledge, insight and experience gained on autopilot and autoland design by interviewing (former) industrial experts and by performing the predesigns for the RealCAM and RealATTAS models will be of great value for future activities in the field of control systems, avionics systems, autopilot developments and certification. NLR is also heavily involved in multi-disciplinary types of projects, like the EU-funded ”a computational design engine incorporating Multi-disciplinary design and Optimisation for Blended wing body configuration (MOB) where process efficiency aspects play a dominant role.

The shell for autoland simulation and evaluation can be used for future supporting activities in the area of autolands subject to the JAR/AWO requirements. The modular set-up of the shell facilitates the inclusion of other aircraft models and new modules. For example, wake vortex modules could be included which can be used and other current and future EU activities such as S-Wake and I-Wake.

AS

An industrial assessment of the RealCAM controllers and a qualitative assessment of the flight tested RealATTAS autoland designs was performed. Results of the project do not show any major ways of improvement compared to today’s autopilot development process. However the project shows interesting techniques for robust design (Multi-model Eigenstructure Assignment, already in use inside AS, and Multi-objective optimisation, under evaluation in AS for new aircraft development). In conclusion, AS has no intention to directly re-apply the software tools set up in the project.

DA

As mentioned before, DA has a high interest in improving the efficiency of its current design processes. The proposed multi-model, multi-objective approach (MOPS), which is based on the standard software tool MATLAB that is used within DA anyhow, has an excellent perspective. It is planned to define certain demonstrator projects of limited complexity for which the applicability and benefit of the method in an industrial environment shall be proven. This is a short term activity. The field of application will not be limited to the design of autoland control laws but extended to control law design in general and to flight mechanical tasks such as tail plane sizing. After successful demonstrations, this design method will be extended to other more complex and multi-disciplinary applications.

DLR

In modelling the application of the aircraft libraries and automatic code generation via Dymola to the REAL project has given important feedback for future extensions and improvements. The two autoland design problems will be further used as benchmarks in development of new flight control design methods.

DLR provided one of the two autoland controllers for each of the benchmarks. Useful experience and know-how was gained in developing a control law architecture for a realistic autoland design problem. Future flight control law design projects (not limited to autoland) will benefit from this. New optimisation strategies and new types of optimisation criteria (i.e. derived from on-line Monte-Carlo analysis using SIMPALE) have been developed that will be further improved and applied in current and future industrial design tasks.

The application of MOPS has given important feedback on how optimisation can be exploited to further improve the efficiency of the (flight) control law design process. Currently, MOPS and the underlying process technology are introduced in several areas of the aerospace industry.

DLR-BS's flying test bed ATTAS was made available for flight testing the DLR and ONERA RealATTAS autoland systems. The capability of easily transferring control laws developed in Matlab-Simulink to the aircraft flight control computer has proven its high value during the REAL project. Limited allowance for using the fly-by-wire mode down to the runway, which was gained in the course of the REAL project, will be extended and intensively used in future flight testing of manual and autopilot flight control laws.

DUT

In WP1 DUT has been actively involved in the set-up of two different benchmark software shells. The availability of these software benchmarks brings the possibility to further improve the educational programmes in the field of control systems and simulations, since REAL provided tools to better evaluate autoland controllers than possible before. DUT works in the theoretical field to develop even more innovative controller design methodologies. These tools will be very supportive in that are.

In WP3 DUT has executed the preliminary designs which gave very useful insight in the real life problems of control systems theory thereby creating the possibility to combine theoretical and practical fields. To DUT's opinion the results of REAL are, of course with some adaptation, transferable to other automotive technology areas as well. For instance aerospace applications like re-entry vehicles.

ONERA

ONERA has developed powerful tools to perform fast Monte-Carlo analysis on both aircraft models. These tools, e.g. ‘SIMPALE’ and ‘SIMPALE-2’, are quite general since a very large number of parameters can be easily changed and saved by the user. A special interface has been developed (based on Real-Time Workshop C-code generation functionality) so that the control law (written in Simulink standard) can be changed very quickly.

ONERA was also highly involved the autoland control systems design where useful knowledge and experience were gained, which, in the future, will allow ONERA to provide more efficient support in autoland system development programme. For example, new approaches are currently studied to improve the flare with turbulence and ground effect, which appeared as a major difficulty in the REAL project.

ONERA is also involved in a teaching program at SUPAERO (National Engineer School in Aeronautics and Space). Here it is important to mention that a simplified project (only including longitudinal control in the approach flight phase) is being executed, and a slightly modified (to avoid any confidentiality problems) version of the REAL is being developed to give the students the opportunity to get more familiar with autoland control systems.

8.2 Dissemination of results

For the REAL project no patent of results was to be expected, so it was regarded very unlikely that particular restrictions on the dissemination of results would become important. All partners agreed to disseminate the results at workshops by presentations and via publications, wherever and whenever possible. The only restriction on this all was not to reveal any company secret data.

Results have been disseminated already at several occasions by DLR such as internal workshops and an RTO congress, 8-11 May, 2000, Braunschweig, Germany and by NLR on the CEC organised “Aeronautical Days”, 29-31 January 2001, Hamburg, Germany.

Other disseminations are still expected such as a to be published inside the conference proceedings of the “Aeronautical Days”. Papers publications are expected in various respectable journals and books. DLR has submitted three papers to the AIAA’s 2001 Guidance Navigation and Control conference. All three were accepted.

8.3 Industrial applications and market analysis

In the REAL project the role of the industrial partners was primarily to assess the (robustness) quality of the controllers delivered by the research parties. At the project’s final evaluation meeting, industry expressed a sincere interest in the transfer of the knowledge obtained and tools developed. Industry stated that they would like to obtain hands on experience with the applied tools, especially with the two robust design techniques used (i.e. Multi-model

Eigenstructure Assignment and Multi-Model Multi-Objective Optimisation), based on the tool MOPS (Multi Object Parameter Synthesis) and furthermore with the tools SIMPALE and SIMPALE2. A project to introduce the new tools into the industrial environment, but to also get some assistance (training) in how to use them was desired. For a future technology project, it was proposed at the final project meeting to build integrated teams consisting of people from research institutes, universities and from industry. However, AS already started themselves to improve their in-house tools including some results of the REAL project (customising internal with optimisation tools etc). This was found less complicated than initially thought, thereby reducing the need for integrated teams on this subject.

9 References

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Appendix A: List of Deliverables of the REAL project

The following section presents an overview of all the deliverables produced in the duration of the project, subdivided in:

- general deliverables, see table A.1,
- contractual deliverables, see table A.2,
- additional deliverables, see table A.3.

Table A.1 General Deliverables

N°	Description
1.	Minutes of the first REAL meeting, May 14&15, 1998, NLR, Amsterdam, The Netherlands, Ref.: BRPR-CT-98-0627/MM-01v1.
2.	Minutes of the second REAL meeting, July 15&16, 1998, AS, Toulouse, France, Ref.: BRPR-CT-98-0627/MM-02v1.
3.	Minutes of the third REAL meeting, October 5&6, 1998, DLR, Oberpfaffenhofen, Germany, Ref.: BRPR-CT-98-0627/MM-03v1.
4.	Minutes of the fourth REAL meeting, January 25&26, 1999, ONERA, Toulouse, France, Ref.: BRPR-CT-98-0627/MM-04v1.
5.	Minutes of the fifth REAL meeting, April 26&27, 1999, TUD-Delft, The Netherlands, Ref.: BRPR-CT-98-0627/MM-05v1.
6.	Minutes of REAL's 1st Technical Meeting, June 21 and 22, 1999, ONERA-CERT, Toulouse, France, Ref.: BRPR-CT98-0627/TM-01v1.
7.	Minutes of the Mid–Term Assessment Meeting of REAL, September 24, 1999, Aérospatiale-Matra Airbus, Toulouse, France, Ref.: BRPR-CT98-0627/MM-MTAv1.
8.	Minutes of the sixth REAL meeting, September 23, 1999, AS, Toulouse, France, Ref.: BRPR-CT-98-0627/MM-06v1.
9.	Minutes of the seventh REAL meeting, December 13&14, 1999, NLR, Amsterdam, The Netherlands, Ref.: BRPR-CT-98-0627/MM-07v1.
10.	Minutes of the eighth REAL meeting, March 13&14, 2000, DA-Hamburg, Germany, Ref.: BRPR-CT-98-0627/MM-08v1.
11.	Minutes of the ninth REAL meeting, June 7&8, 2000, DLR, Braunschweig, Germany, Ref.: BRPR-CT-98-0627/MM-09v1.
12.	Minutes of the tenth REAL meeting, September 25&26, 2000, ONERA, Toulouse, France, Ref.: BRPR-CT-98-0627/MM-10v1.

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Table A.1 General Deliverables

N°	Description
13.	Minutes of the eleventh REAL meeting, December 12, NLR, Amsterdam, The Netherlands, Ref.: BRPR-CT-98-0627/MM-11v1.
14.	Minutes of the Final REAL meeting, December 13, 2000, NLR, Amsterdam, The Netherlands, Ref.: BRPR-CT-98-0627/MM-FMv1.
15.	REAL project web site to support the technical and management activities, accessible to REAL project members only. Web site active since October 1998.
16.	REAL public web site for dissemination of results: http://www.nlr.nl/public/hosted-sites/real/index.html
17.	CD-ROM containing the REAL project deliverables

Contractual Deliverables

The table A.2 starting on next page presents an overview of the contractual deliverables sent out to the CEC.

Some deliverables have been combined after approval by the CEC. If this is the case, both deliverable numbers are given in the list.

Table A.2 Contractual Deliverables

N°	Description
D0.1	1st Six Monthly Progress Report, May 1,1998- November 1,1998. Ref.: BRPR-CT98-0627/SR-01v1, November 30th, 1998.
D0.2	1st Twelve-Monthly Progress Report, May 1,1998 – April 30, 1999. Ref.: BRPR-CT98-0627/TR-01v1, May 25th, 1999.
D0.3	• Mid-Term Assessment Report, version 1, May 1, 1998 – July 31, 1999. Ref.: BRPR-CT98-0627/MA-01v1, August 31st, 1999. • Mid-Term Assessment Report, version 2, May 1, 1998 – July 31, 1999. Ref.: BRPR-CT98-0627/MA-01v2, January 31st, 2000.
D0.4	2nd Six-monthly Progress Report, May 1, 1999 – October 31, 1999. Ref.: BRPR-CT98-0627/SR-02v1, December 20th 1999.
D0.5	2nd Twelve-Monthly Progress Report, May 1,1999 – April 30, 2000. Ref.: BRPR-CT98-0627/TR-02v1, July 14th, 2000.
D0.6	3rd Six-monthly Progress Report, May 1, 2000 – October 31, 2000 Ref.: BRPR-CT98-0627/SR-02v1, February 22nd, 2001.
D0.7	• REAL Exploitation Report, Ref.: BRPR-CT98-0627/ER-01v1, March 30th, 2001.
D0.8	• REAL Publishable Synthesis Report, Ref.: BRPR-CT98-0627/PSR-01v1, June 28th, 2001.
D1.1	• RealCAM Benchmark Definition, version 1.0, Ref.: BRPR-CT98-0627/TP-01v1, December 31st 1998. • RealCAM benchmark software v1.0. • RealCAM Benchmark Definition, version 2.0, Ref.: BRPR-CT98-0627/TP-01v2, July 6th, 2001. • RealCAM benchmark shell software final version v4.0
D1.2	• RealATTAS Benchmark Definition, Ref.: BRPR-CT98-0627/TP-04v1, December 21st, 2000 • RealATTAS benchmark software final version 2.4
D2	• Autopilot Design Process Study, BRPR-CT98-0627/TP-02v1, October 1998.
D2A	• Typical Aspects of the Industrial Autoland Control Law Design Process, Ref.: BRPR-CT98-0627/TP-02Av1, March 29th 1999. (originally part of D2)
D3.1	• The RealCAM Predesign, Ref.: BRPR-CT98-0627/TP-03v1, June 11th, 1999. • RealCAM predesign software version 1.0
	Table continues on next page

Table A.2 Contractual Deliverables

N°	Description
D3.2a/ D4.1a	• RealCAM: ONERA Design Report, Ref.: BRPR-CT98-0627/TP-05v1, December 20th, 2000. • ONERA RealCAM controller software, version v1.0
D3.2b/ D4.1b	• RealCAM: DLR Design Report, Ref.: BRPR-CT98-0627/TP-06v01, December 22nd, 2000. • DLR RealCAM controller software, version v1.0
D3.3	• The RealATTAS predesign, Ref.: BRPR-CT98-0627/TP-07v1, December 22nd, 2000. • RealATTAS predesign software, version v1.0
D3.4a/ D5.1a	• RealATTAS: ONERA Design Report, Ref.: BRPR-CT98-0627/TP-08v1, December 12th , 2000. • ONERA RealATTAS controller software, version v1.0
D3.4b/ D5.1b	• RealATTAS, DLR Design Report, Ref.: BRPR-CT98-0627/TP-09v1, April 24th, 2001. • DLR RealATTAS controller software, version v1.0
D4.2/ D5.2	• Industrial Evaluation Report, Ref.: BRPR-CT98-0627/TP-10v1, 2001.
D6.1/ D6.2	• REAL Project Control Document, Ref.: BRPR-CT98-0627/ME-01v1, October 30th, 1998.
D6.3	• Final Technical Report of the REAL project, Ref.: BRPR-CT98-0627/FTR-01v1, June 18th, 2001.

Additional Deliverables

The table A.3 below lists the additional technical deliverables produced within the project.

Table A.3 Additional Deliverables

N°	Description
1.	AS Technical note 518.0896/98:Design objectives
2.	AS Technical note 518.1101/98: Aircraft models
3.	TN-01, "REALCAM Technical Note on the Autoland Mission Requirements", Ref.: BRPR-CT98-0627/TN-01v2, June 25th, 1999.
4.	TN-02, "Assessment of Autoland Control Law Design Procedures in the REAL Project", Ref.: BRPR-CT98-0627/TN-02v2, July 13th, 1999.
5.	TN-03, "RealCAM-SIMPA Open-Loop Analysis", Ref.: BRPR-CT98-0627/TN-03v1d1, August 22nd, 2000.
6.	TN-04, "Assessment of Autopilot Design Processes", Ref: BRPR-CT98-0627/TN-04v1, December 15th, 2000.
7.	TN-05, "Flight Test Data and Evaluation of Autoland Controllers", BRPR-CT98-0627/TN-05v1, 2001.
8.	TN-06, "Assessment of Autoland Control Law Design Performance", Ref: BRPR-CT98-0627/TN-06v1, 2001.