TOOLS FOR DESIGN AND SIMULATION OF UAV FLIGHT CONTROL

J. Bals, H.-D. Joos, G. Looye, A. Varga
Deutsches Zentrum für Luft- und Raumfahrt (DLR)' Institute of Robotics and Mechatronics
D-82234 Wessling, Germany
E-mails {Johann.Bals,Dieter.Joos,Gertjan.Looye,Andras.Varga}@dlr.de

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Abstract: *High performance and robustness requirements for autonomous UAV flight control systems and stringent requirements for short and cost effective design cycles increase the necessity for an efficient computer aided control law design process using advanced control design methods and tools. This paper describes a model and optimization based flight control law design process, which can be applied to a wide range of vehicle classes. The design process is based on multi-physical, object-oriented flight dynamics modeling using the modeling language Modelica and on a multi-objective parameter optimization environment. A generic Modelica flight dynamics library allows modular composition of new parameterized vehicle models and efficient simulation code generation for specific use cases. Multi-objective optimization is used for tuning the free parameters in linear or nonlinear flight control laws. Thereby, given requirements for stability, trading structural loads and other physical limitations are formulated as computational design criteria. Robustness to uncertain parameters can be addressed via robustness measures, via a multi-model and multi-case approach, and via statistical Monte-Carlo based criteria. In the assessment step of the design process worst-case optimization w.r.t. uncertain parameters is applied for systematically detecting weaknesses of the control law design. The successful application of the design process to civil transport and high performance military aircraft is demonstrated and the applicability for UAV flight control design is discussed.*

1. INTRODUCTION

For the successful development, acceptance, and operation of future Uninhabited Air Vehicles (UAVs), control and automation are among the most important enabling technologies, together with others like materials, structures, propulsion and aerodynamics. As illustrated in Figure 1, control and automation covers the entire hierarchical levels bottom up from local control of engines and actuators (I), stability augmentation (II) , autopilot control laws (III: airspeed hold, altitude hold, etc.), guidance and navigation control loops (IV: automatic take-off and landing, climb and descent, cruise, etc.), autonomous onboard vehicle management (V: health monitoring, fault tolerance, environmental situation handling), and onboard/ground mission management (VI).

The design of control functions for layers II - IV is mainly driven by the flight dynamics and automatic flight control domain and is the main focus of this paper. As for conventional aircraft the stability augmentation loop II has to satisfy robust stability and additional dynamic requirements over the entire operating envelope of the vehicle. Typical additional aspects to be taken into account are attitude (rate) tracking, control effort, structural loads, flutter margin. The UAV autopilot control modes in layer III contain, similar to conventional aircraft, path and speed tracking functions, including airspeed, altitude, vertical speed hold, etc. Layer IV also contains the same functionality as for piloted aircraft, although navigational means will more rely on systems such as GPS.

Generally speaking, the functionality to be implemented in layers II - IV for UAVs is more or less the same as for automated systems on board of modern fly-by-wire military and civil transport aircraft. The difference is mainly in the design guidelines and detailed performance specifications to be followed in the design and parameter tuning of the individual control laws. For example, the absence of piloted manual controls (unless the aircraft is piloted remotely) and the absence of passengers on board allow to reduce or even neglect handling quality and ride comfort requirements specifications. On the other hand, additional design and tuning criteria arise from specific UAV mission and payload requirements like pointing accuracy of observation sensors. These additional criteria have to be compromised with physical and flight dynamical constraints of the vehicle. For UAVs the tendency is to drive the control law design very close to the limits of flight physics, structural dynamics and flutter with less margins left.

For aircraft with fly-by-wire technology time and cost associated with control law development has become a critical issue. Due to stringent requirements for short design cycles and affordable UAVs there will be an increased necessity for an efficient, automated, computer aided control law design process using advanced control design methods and tools. Due to an increased use of model and simulation based design and assessment, the handling of model and flight uncertainties through the design process is most important.

All of the above aspects have been considered in a technology requirements analysis "UAVs: Enabling Science for

Military Systems" [21] performed by the US Air Force resulting in the following recommendation:

"In light of the special factors driving the design of UAVs, the U.S. Air Force should strengthen its support for basic research programs addressing the rapid (automated) design and implementation of high-performance control laws. Areas of interest include basic theory for nonlinear and adaptive control, reusable control law structures and processes capable of full-envelope design, software tools for automated control design and analysis, automated code generation from high-level design tools, and simulation models with sufficient fidelity for affordable tests and verifications."

In this paper a design process is proposed that is based on the multi-physical, object-oriented modeling technology Modelica and on multi-objective optimization. Object-oriented modeling technology allows for convenient development of multi-disciplinary vehicle models using standard libraries, from which highly efficient runtime simulation code for design optimization and assessment can be generated. The use of multi-objective optimization on one hand allows for fast design cycles, since control law tuning becomes more automated and the formulation of design criteria is very purposeful. Furthermore, robustness can be addressed in various ways, resulting in robust control laws and avoiding or reducing the need for design iterations related to model uncertainty. The methodology can also handle any controller architecture, allowing proven structures and experience to be re-used. On the other hand, multi-objective optimization can be used to efficiently detect design weaknesses by means of worst-cases robustness analysis (assessment).

This design process has been successfully applied to several challenging flight control design problems [14], [6], [3], [4] involving modeling, design and assessment of primary as well as secondary flight control laws, such as autopilot functions and active loads alleviation functions [10]. Due to its capabilities to model the nonlinear aircraft dynamics and its uncertainties and to explicitly consider given design specifications in the optimization based control law tuning and final robustness assessment, the proposed design process with the underlying methods and tools is also well suited for design and simulation of future UAV flight control laws.

This paper is structured as follows. In section 2 the DLR flight control design process is described including modeling, design optimization, and assessment. In section 3 an application example of an automatic landing control laws design project for a civil transport aircraft is given. One important aspect of this example is the generic controller structure which is based on nonlinear dynamic inversion and partly on the Total Energy Control System (TECS). A second aspect is the systematic tuning of the control law parameters using multi-criteria optimization in combination with Monte-Carlo analysis for robustness criteria computation. The main focus of the military application example in section 4 is the assessment of flight control laws using worst-case optimization techniques. In section 5 conclusions are drawn.

2. DESIGN PROCESS

The DLR flight control laws design process is based on object-oriented modeling, multi-objective optimization of free parameters within a (nonlinear) controller architecture that is specified by the designer, and optimization based assessment. The over-all design process is depicted in Figure 2. The principal steps, shown to the left, will be explained in the following subsections. To support the process, software tools and methods have been developed. These are depicted to the right.

2.1 Aircraft modeling

For analysis and design computations, efficient parameterized models of the aircraft and system dynamics are required. Although the proposed design process is open to interface with any simulation platform, for many applications the development of design models is part of the process. For this reason, we support model development using the object-oriented modeling language Modelica [19], [20]. Modelica has been designed for modeling of complex, physical systems. With help of the program package Dymola [2] (Dynamic Modeling Laboratory) models may be composed graphically in so-called object diagrams, using drag and drop from component libraries. To this end, a comprehensive set of Modelica-based model libraries is available for engineering domains such as electronics, control, multi-body mechanics, drive trains, etc. For flight control law design and simulation, an extensive flight-dynamics class library [15] is available. Figure 3 depicts an object diagram of a civil aircraft, constructed from this library. Since components from any library may be combined into a single object-diagram, Modelica is an inherently multi-disciplinary modeling language. For UAV applications, the Flight Dynamics Library allows for efficient composition of aircraft models. For the development of aircraft-specific model components, such as the aerodynamics, base classes are available from which these components can be implemented quickly.

An important feature of object-oriented modeling is separation between model composition, and model application, see Figure 4. In this way, the user may enter model equations in their physical form, without the need to bring 'unknowns' to the left hand side, and interconnections between model objects are not limited to one directional signal flow, as is the case in most block-oriented modeling packages. After the model has been composed, the user has to specify inputs, outputs, and parameters that may be set from outside the model, as required for the intended application. Dymola (as a Modelica "compiler") then sorts and solves the equations according to the specified inputs and outputs using a highly sophisticated symbolic engine and generates fast simulation code in the form of Ordinary Differential Equations (ODEs) or Differential Algebraic Equations (DAEs). The generated c-code may be linked for simulation within Dymola, or with external simulators such as Matlab/Simulink [18].

The freedom to designate model variables as inputs or outputs not only allows for generation of efficient simulation code, but also for automatic generation of inverse model code. This is highly valuable for inverse model simulation, very fast model trimming, as well as development of control laws based on inverse model equations, such as Nonlinear Dynamic Inversion [13].

2.2 Controller structure synthesis

Controller architecture selection and controller parameter tuning are fully independent. The architecture is selected by the designer and therefore open to incorporate all available knowledge and experience. It may be linear (e.g. resulting from synthesis methods) or nonlinear and is often specified in Matlab/ Simulink. The Simulink add-on Real-Time Workshop (RTW) can be used to automatically generate code for implementation in for example dedicated Monte-Carlo simulation tools, or as prototype software in test hardware (e.g. in-flight simulator).

For the control levels II to IV (see Figure 1) proven structures exist. For the inner loops (level II), Nonlinear Dynamic Inversion (NDI) is a promising methodology, also for UAVs. NDI provides good decoupled tracking performance and automatic gain scheduling, resulting in uniform performance over the flight envelope. The method is based on inverse model equations in the control laws, which are easily adapted for new aircraft configurations. In case the aircraft model is available in Modelica, NDI control laws can be generated automatically, as outlined in Figure 4. For the tracking loops (level III), generic structures such as the Total Energy Control System (TECS) [11] can be incorporated in the architecture.

2.3 Multi-objective parameter optimization

Control law design problems are often multi-disciplinary in their nature where many different, often conflicting design requirements have to be fulfilled simultaneously. In the case of many design objectives the control systems designer needs to compare different design alternatives. Further, he needs to know to which extent certain design objectives are satisfied and in case of conflict, he needs quantitative information about degradation of individual objectives while other objectives are improved.

Design objectives can usually be expressed as mathematical criteria representing quantitative measures of achieved performance. The solution of such a control design problem with many criteria can be carried out by solving a multi-objective optimization problem. As a computer aided design technology, multi-objective optimization-based design is able to address all design goals and constraints simultaneously, while compromising them individually according to given demands. Due to the complexity of the design task, a multi-objective optimization-based design usually involves experimenting with different set-ups for criteria formulation and weighting, different controller structures and parameterizations, as well as alternative (e.g. global or local) optimization methods.

The multi-objective optimization problem is solved by min-max parameter optimization utilizing the design environment MOPS (Multi-Objective Parameter Synthesis) [7], [8]. MOPS is primarily based on the widespread technical computing environment MATLAB [17] taking advantage of the powerful MATLAB-language features, like flexible data structures and handle graphics. The employed optimization solvers are proprietary codes implementing several powerful algorithms. MOPS explicitly supports, in a general controller design process as it is illustrated in Figure 2, features like multi-model/multi-case design problems, robustness assessment, distributed computation, Monte-Carlo simulation etc.

A complex design task, like UAV flight control law design, has to be split into several sub-tasks. This can be induced by the adopted modular controller architecture. Sub-tasks for following acceleration/rate commands, maintaining altitude/speed/heading, automatic take-off/landing, flight path tracking loops, guidance modes etc. can be defined. For these sub-tasks the appropriate computational models, including maneuvers, disturbances and design criteria have to be formulated. Sub-tasks can be designed individually in MOPS, but for ending up with a balanced, less complex control law these sub-tasks should also be considered in combination. Combining several sub-tasks to an overall design problem is explicitly supported by the multi-model feature of MOPS.

Robustness as an important aspect of control law design can be addressed by appropriately mapping the requirements into design criteria [14] or via the multi-case approach. For example, for models depending on uncertain parameters, the robustness against parameter variations can be achieved by trying to apply a unique controller to a whole set of model instantiations, corresponding to different values of physical parameters. Such a set of model instantiations is called a *multi-case model* and ideally covers essential variations of dynamics and operating conditions. MOPS explicitly supports the multi-case approach for robust controller design, by automatic generation of multi-case models from a given parameterized computational model.

Optimization requires a thorough formulation of design objectives through smooth optimization criteria. A set of basic functions for the most commonly used time and frequency domain criteria is provided within a MOPS criteria library, which may serve as a basis to define more complicated application oriented design criteria. To compare criteria in a multi-objective optimisation problem, a proper normalisation of criteria is necessary via appropriate transformations. MOPS provides a convenient framework to normalize automatically criteria by generating appropriate scaling and shifting on basis of specified good/bad limiting values (similar to fuzzy logic membership functions) [7]. The criteria transformations ensure the separation between the 'acceptable' and 'not acceptable' values with respect to a normalized value of one. All best possible values are mapped to zero, i.e. to the smallest criterion value, see Figure 5.

2.4 Controller 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 optimization, i.e. for given designed controller parameters T^* the worst-case model parameters p^* are searched such that a selected performance criterion, e.g. stability margin, is as bad as possible. Worst-case models may serve to update the set of cases used for multi-case robust design [1].

The basic requirements for the applicability of the optimization-based assessment approach are the availability of suitable parametric models describing the overall non-linear dynamics of the augmented vehicle and of accompanying efficient trimming, linearization and optimization software tools. Especially there is no limitation with respect to assessment criteria, being able to address all kind of clearing requirements which are expressible as mathematical criteria. The optimization-based assessment approach proposed here [4], can be seen as a combination of gridding-based classical search in a discrete set of flight conditions with the optimization-based continuous search for worst-case parameter combinations in the complete parameter space.

3. APPLICATION EXAMPLE: AUTOMATIC LANDING CONTROL LAWS DESIGN

The DLR design process and software tools have been successfully used in many aerospace and robotics applications. In this section we will discuss an application to the design of automatic landing (autoland) control laws, which of course will be an important functionality of any autonomous UAV. In the frame of the project REAL (Robust and Efficient Autopilot control Laws design) [16], funded by the Commission of the European Union, two design teams, one from ONERA, one from DLR each had to deliver two autoland designs for two dissimilar aircraft. Main objective of REAL was to demonstrate how modern robust control design methods may improve the efficiency of the autopilot control laws design process. The first design was performed for a large civil transport aircraft called RealCAM (REAL Civil Aircraft Model), during which the design teams were allowed to fine-tune their processes to specific issues and requirements involved with automatic landing. The second design, for DLR's Advanced Technologies Testing Aircraft System (ATTAS), was intended to test design process efficiency. The design had to be delivered in a very short time frame and was implemented in ATTAS and flight tested, obviously demanding high quality of the control law.

Modeling

As discussed in section 2, the first stage in the design process involves the development of design models of the aircraft and on-board systems. To this end, the generic transport aircraft model RealCAM and DLR's fly-by-wire test bed ATTAS were implemented in Modelica, using the DLR Flight Dynamics Library, see Figure 3. The simulation code generated from Dymola was linked with a Simulink environment in which the control laws were developed. Trimming of the models was done using an inverse model, automatically generated from the same model implementation as outlined in Figure 4.

Controller structure synthesis

The adopted over-all controller structure is depicted in Figure 6. Three main loops can be identified, separated by the vertical dashed lines: inner loop for stability and command augmentation (level II), path tracking loop (level III), and guidance loop (level IV). The task of the inner loop is to improve stability and to achieve robust tracking of command variables (ϕ_c ,θ_c, $\dot{\psi}_c$). This part of the controller was designed with Nonlinear 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) [11] 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 [12], 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 center 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 localizer (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 were automatically derived from the aircraft model in Modelica by swapping inputs and outputs and utilizing Dymola's code generator, see Figure 4.

Design optimization

The design cycle for tuning the control laws is depicted in Figure 7. Inner, tracking, and guidance loops were designed sequentially. However, to improve over-all system performance, for optimization of each sequential loop, design parameters in previous loops were allowed to be adjusted by the optimizer, eventually leading to simultaneous optimization of all control law functions.. For each controller component an optimization sub-task was defined. This involves modeling of the selected architecture (right) and selection of appropriate design criteria for tuning and compromising (left).

For tuning of the flare and glide slope modes the Monte-Carlo analysis software, called SIMPALE, was incorporated into the optimization. Risk values were directly addressed as optimization criteria, see Figure 5. In this way an acceptable solution was found automatically, whereas otherwise fulfilling average risk requirements turned out to be difficult to achieve. Nominal performance is addressed via criteria from a single landing simulation, robust performance with respect to aircraft configuration, airport and atmospheric parameter variations is addressed via Monte-Carlo analysis.

After the RealCAM design was finished, the controller structure was tuned for ATTAS using the developed optimization set-ups in only a few weeks, demonstrating a very short design cycle for a dissimilar aircraft. The ATTAS design was successfully flight tested during six automatic landings. Both the RealCAM and ATTAS designs fulfilled practically all performance and robustness requirements, based on JAR-AWO specifications [5].

4. APPLICATION EXAMPLE: OPTIMISATION-BASED CLEARANCE OF FLIGHT CONTROL LAWS

The clearance of control laws can be seen as the last step of the flight control system design, taking place when a mature controller design is available and ready for flight tests. In the clearance process it has to be proven that the flight control laws have been designed such that the aircraft is safe to fly throughout the whole flight envelope, under all parameter variability and failure conditions. The Group for Aeronautical Research and Technology in Europe (GARTEUR) has established in 1999 the Flight Mechanics Action Group 11, FM(AG11), to investigate the potential benefits of using advanced analysis methods for the clearance of flight control laws. This group focused on the improvement of current industrial clearance process of the flight control laws by employing a range of new methods able to address linear and nonlinear robustness analysis problems. DLR was involved in this research by addressing clearance problems via optimization-driven worst-case search. The main goals were to demonstrate the applicability of this approach to arbitrary clearance criteria (linear or nonlinear), without restrictions on the maximal number of simultaneously analyzed uncertain parameters, and to illustrate the increased reliability of this approach in locating reliably worst-case parameter combinations, even in the case when some worst-case parameter values lie strictly inside their uncertainty bounds. Note that the classical industrial approach based on parameter gridding techniques has strong limitations. Because of exponential complexity of gridding-based search, the classical approach is restricted to handling at most 8-9 uncertain parameters simultaneously. Moreover, this method is not able to locate worst-case parameters combinations which are different form their extreme values.

The optimization-based approach has been successfully applied to a clearance benchmark problem consisting of the generic fighter model HIRM (High Incidence Research Model) augmented with a controller based on Robust Inverse Dynamics Estimation (RIDE). For the clearance of the closed-loop HIRM+RIDE configuration, several analysis criteria have been defined covering stability (Nichols stability margin and unstable eigenvalues criteria), handling (average phase rate and absolute amplitude criteria) and nonlinear dynamic performance (largest exceedance of nominal values of the angle of attack (AoA) and normal acceleration). From the HIRM flight envelope, 8 representative flight conditions have been selected (see Figure 8), where robustness analysis has been performed for two sets of uncertain parameters: a small set with 5 longitudinal and 6 lateral axis uncertain parameters, and a full set of 9 longitudinal and 15 lateral axis uncertain parameters, respectively. For linear analysis criteria, the range of values of the AoA was [–15°, 35°]. The goal of the analysis was to identify all flight conditions in terms of Mach number, altitude, and AoA, and all combinations of uncertain parameters where the clearance criteria are most violated.

The obtained analysis results presented in [22] and the industrial evaluation of the analysis results [9] performed by the industrial partner involved in AG11, revealed that among all applied analysis methods (including the classical gridding-based search), the optimization-based approach was the only able to handle the full parameters sets as well as all defined clearance criteria. The importance of this aspect can be seen from Figure 8, where cumulative clearance results for all linear stability and handling criteria are presented [22]. While the HIRM+RIDE control configuration possesses satisfactory performance for quite wide ranges of values of the AoA α when considering the small parameter set, this is not anymore true when considering the full set of 24 uncertain parameters. In this latter case, the cleared AoA ranges are drastically reduced, and the results show that practically the HIRM+RIDE system can not be considered cleared. Such a result was not possible to be obtained by using any other of the employed analysis methods.

5 CONCLUSIONS

The DLR flight control design process uses the multi-physical, object-oriented modeling technology for modeling the flight dynamics and its uncertainties. For specific applications vehicle models are composed using a generic Modelica flight dynamics library. Efficient simulation code can be automatically generated for open and closed loop analysis, for trimming of the aircraft, and for nonlinear control laws like Nonlinear Dynamic Inversion. The multi-objective optimization environment MOPS is used for control law parameter tuning w.r.t. given design requirements. Robustness to uncertain or varying parameters can be achieved by using the multi-model and multi-case features of MOPS and by formulating robustness criteria like gain/phase margins and JAR-AWO risk criteria. In the robustness assessment step optimization based search for design weaknesses is involved.

The results presented in section 3 and 4 for realistic civil transport and high performance military aircraft applications demonstrate the effectiveness of the design process and its methods and tools. Due to its modularity and flexibility the design process has great potential for planned UAV applications and for accommodating specific design rules and guidelines.

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FIGURES

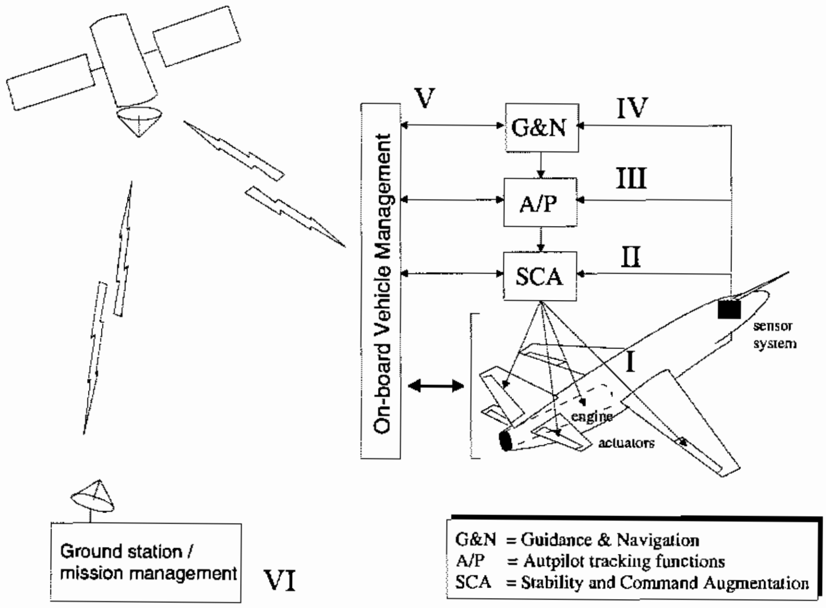


Figure 1: Hierarchical levels of control and automation within UAV system

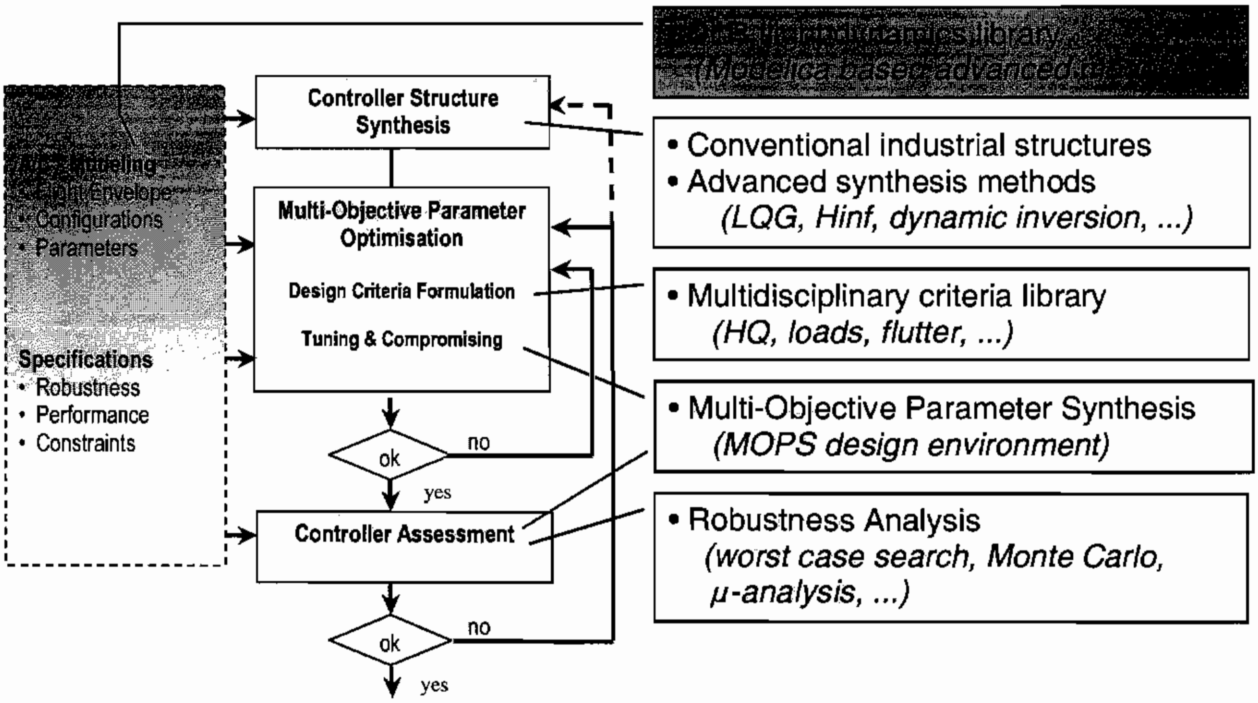


Figure 2: DLR design process with supporting synthesis and analysis tools and methods.

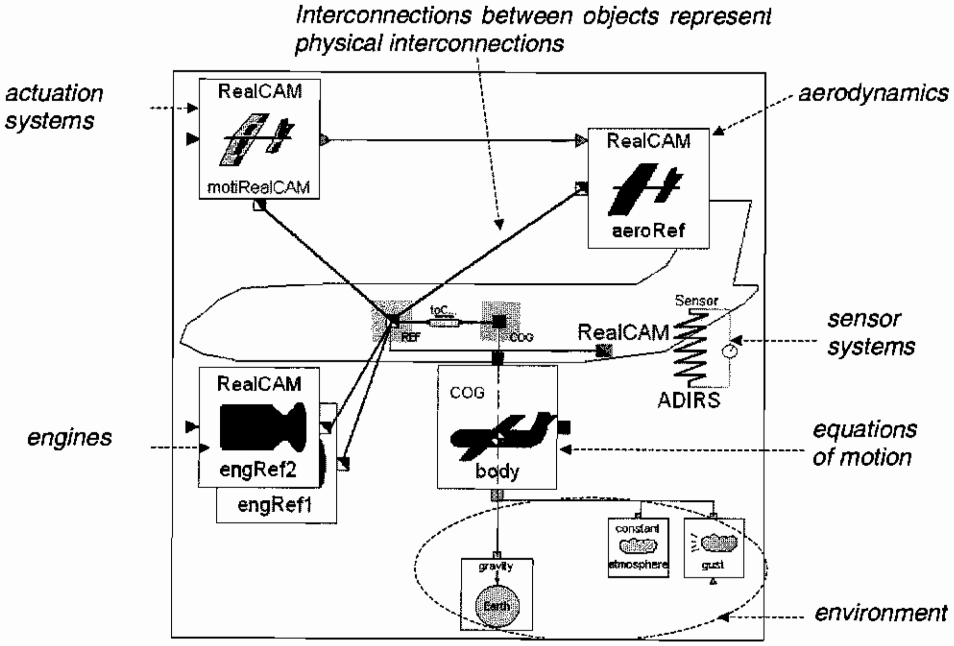
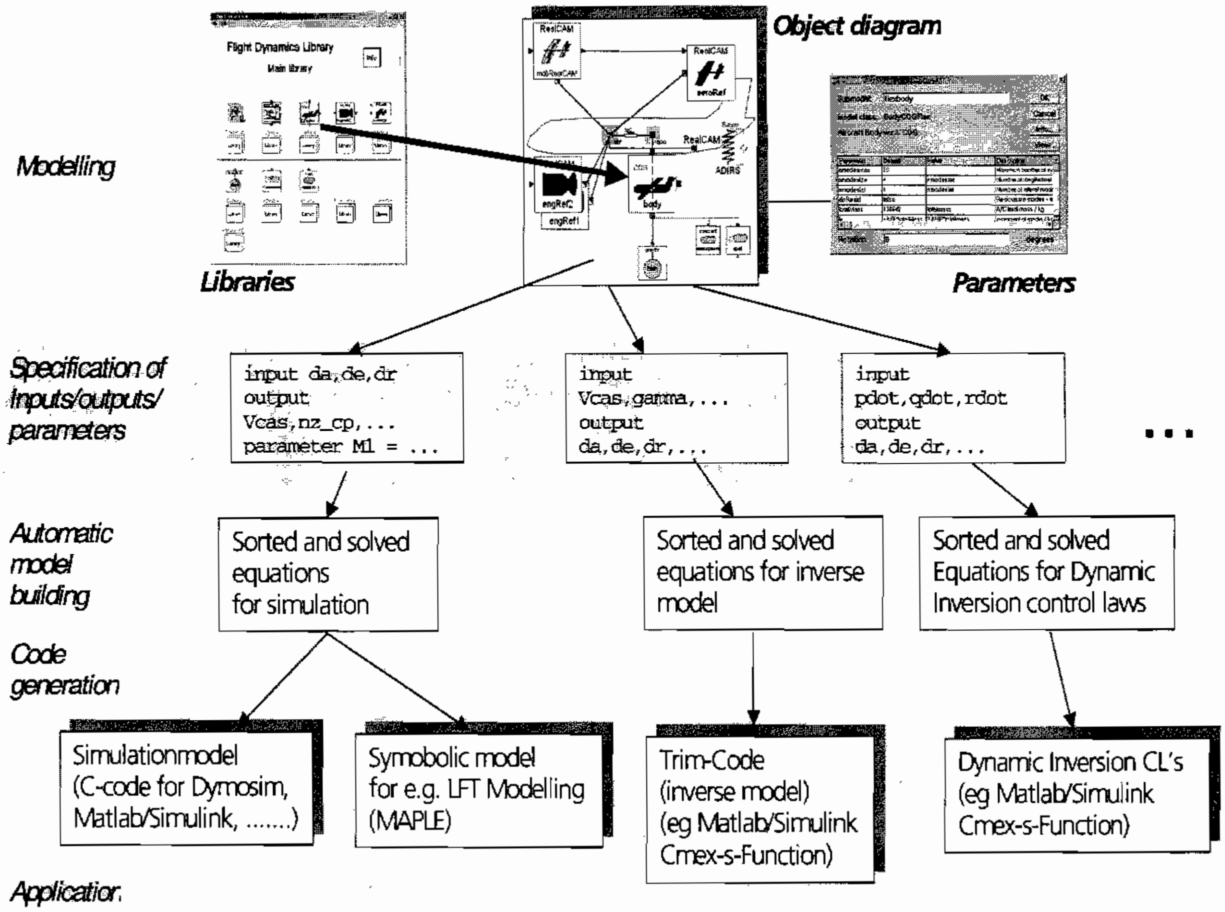


Figure 3: Modelica object diagram of an aircraft model.



```
input da,de,dr
output
Vcas,nz_cp,...
parameter M1 = ...
```

```
input
Vcas,gamma,...
output
da,de,dr,...
```

```
input
pdot,qdot,rdot
output
da,de,dr,...
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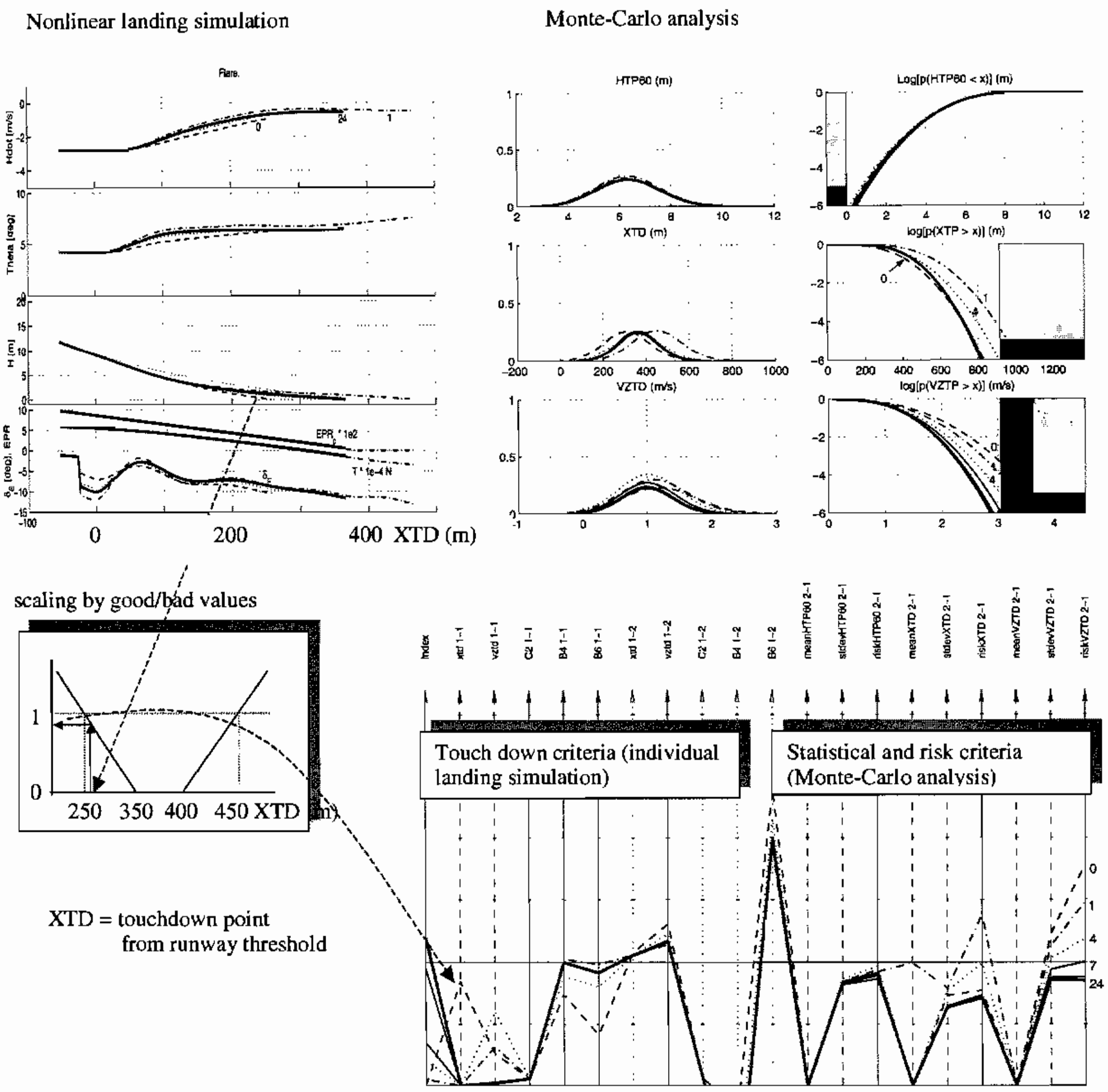
Figure 4: Model building process using Dymola. A model is composed from Modlica libraries. Based on inputs, outputs and parameters as specified by the user, Dymola automatically sorts and solves the model equations and generates code for the intended application.


Nonlinear landing simulation

Monte-Carlo analysis

scaling by good/bad values

XTD = touchdown point from runway threshold

Figure 5: On-line visualization during optimisation with MOPS. Landing performance criteria are computed from non-linear simulation (top left) and Monte-Carlo analysis (top right). For example, touchdown distance is transformed to a mathematical optimisation criterion using good/bad values (below left). The complete set of scaled criteria values is displayed in parallel co-ordinates (below right). Each vertical co-ordinate arrow corresponds to a specific criterion like touchdown distance. In all diagrams, lines and curves (solid, dashed, dotted, ...) correspond to intermediate values of the tuning parameters.

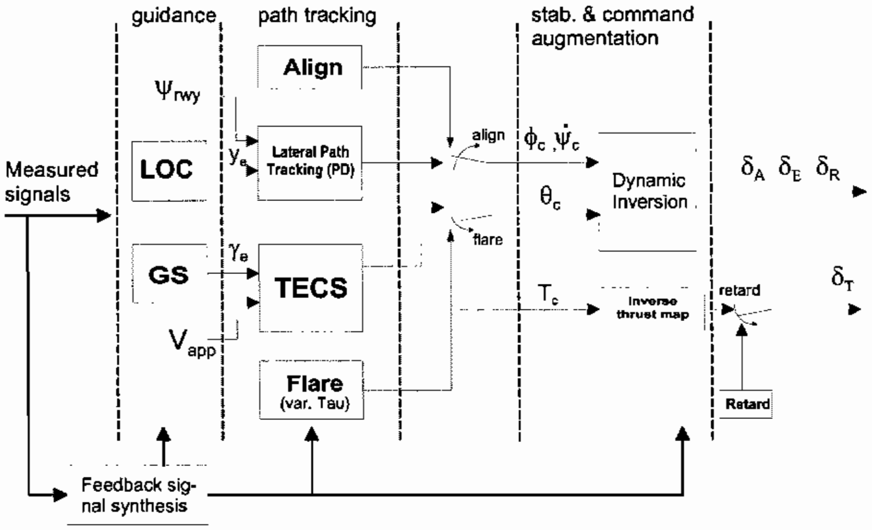


Figure 6: DLR autoland controller architecture

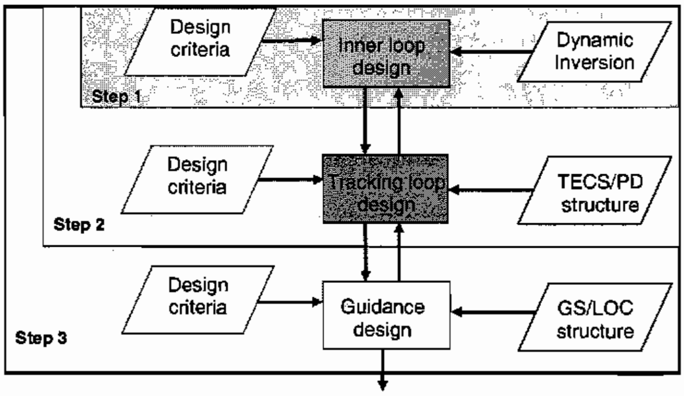


Figure 7: Sequential and combined tuning of inner, tracking and guidance loops.

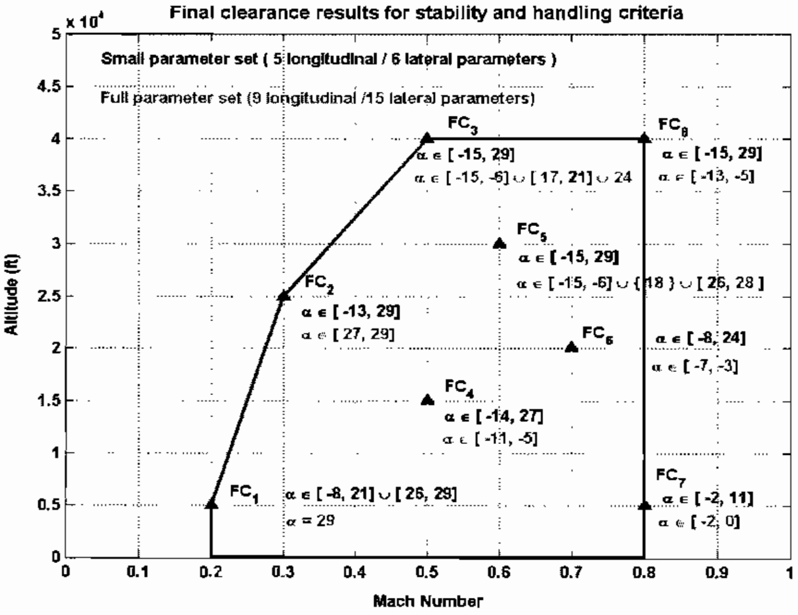


Figure 8: Linear analysis clearance results for HIRM+RIDE. For example, in flight condition FC_2 only an AoA α between 27 and 29 degrees can be cleared if the full set of parameters is allowed to vary. Conventional gridding is possible only for a small parameter set, pretending to clear a much wider range.