



Evaluation of Intelligent Flight Control Systems for Loss-of-Control Recovery and Prevention

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Abstract

Recent advancements in the field of loss-of-control recovery and prevention include fault-tolerant control, improved pilot training, and cockpit automation. The benefits of fault-tolerant "intelligent" flight control systems were demonstrated by the Flight Mechanics Action Group on Fault-Tolerant Control of the Group for Aeronautical Research and Technology in Europe. By assessing one of these systems in actual operational scenarios, the research allowed for an improvement in the systems' technological readiness level. The handling characteristics findings of a piloted flight simulator assessment with a damaged aircraft model demonstrated that an online physical model identification approach contributed to improved pilot performance following potentially catastrophic structural and flight-critical system failures. Airlines and engineering test pilots had no problems conducting a safe approach and landing following the failures and subsequent control reconfiguration by the intelligent flight control system.

Introduction

Various number of measures is currently being taken by the international aviation community to prevent loss-of control (LOC) accidents due to in-flight failures, structural damage, and upsets. LOC is caused by inadequate pilot response (e.g., incorrect stall and recovery procedures), technical malfunctions, or atmospheric upsets and it has become a main cause of aircraft accidents. Fault-tolerant flight control (FTFC), or intelligent flight control, is a technology solution aimed to prevent LOC by exploring the remaining physical capability of the aircraft to still fly. FTFC leads to improved survivability and ability to recover from adverse flight conditions by intelligent utilization of the control authority of remaining control effectors (including the engines). Reconfigurable control strategies allow us to establish stable equilibrium conditions and required maneuverability for safe approach and landing. Motivated by several aircraft accidents at the end of the 1970s, research on self-repairing, or reconfigurable faulttolerant flight control, was initiated to accommodate in-flight failures. Many examples on this paper show the useful of intelligent flight control and how its strategies might save aircrafts from dangerous situations. This paper describes the steps involved in conducting pilot-in-the loop experiments of new intelligent flight control systems for LOC recovery and prevention, starting from the aircraft simulation model development, validation, and verification to experimental design for handling qualities testing and flight control computational load assessment.

RECOVER Aircraft Simulation Benchmark

Benchmark Aircraft Accident Case

The work was focused on the accident of the El Al Flight 1862, a Boeing 747- 200F on 4th October 1992 near Amsterdam Schiphol Airport after the separation of both right-wing engines (engine nos.3 and 4). In an attempt to return to airport for an emergency landing, the aircraft flew several right-hand circuits in order to lose altitude and to line up with the runway, as intended by the crew. During the second lineup, the crew lost control of the aircraft. As a result, the aircraft crashed. The analysis from the first investigation concluded that, given the performance and controllability of the aircraft after the separation of the engines, a successful landing was highly improbable. Figure 2 shows the accident aircraft before takeoff at Amsterdam Schiphol Airport and the reconstructed loss of control trajectory, based on flight data following separation of the right-wing engines.

In 1997 a second investigation was performed independently to analyze of the accident. In

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Figure 2: EL A1 Flight 1862, B747-200F, Amsterdam, 1992 (copyright Wernet Fischdick, Netherlands Aerospace Centre/NLR).

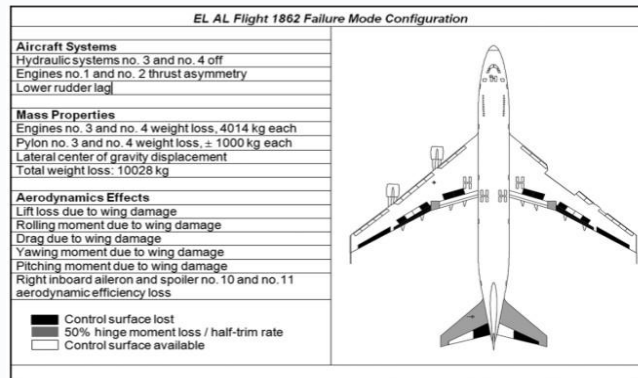


Figure 3: Failure modes and structural damage configuration of the EL A1 Flight 1862 accident aircraft.

contrast to the analysis performed by the Netherlands Accident Investigation Bureau, the parameters of the DFDR were reconstructed using comprehensive modeling, simulation, and visualization techniques. In this alternative approach, the DFDR pilot control inputs were applied to detailed flight control and aerodynamic models of the accident aircraft. The purpose of the analysis was to acquire an estimate of the actual flying capabilities of the aircraft and to study alternative (unconventional) pilot control strategies for a successful recovery. The analysis of the constructed model of the aircraft, as used for the GARTEUR FM-AG(16) benchmark, indicated that, from a flight mechanics point of view, the Flight 1862 accident aircraft was recoverable if unconventional control strategies would have been used. The El Al Flight 1862 damage configuration to both the aircrafts structure and onboard systems, including partial loss of hydraulics and change in aerodynamics after the separation of both right-wing engines, is illustrated in Figure 3.

An analysis of the engine separation dynamics concluded that the sequence was initiated by the detachment of the right in board engine and pylon (engine no.3) from the main wing due to a combination of structural overload and metal fatigue in the pylon wing joint.

Aircraft Model Development and Validation

The DFDR of the El Al Flight 1862 accident aircraft was recovered in a highly damaged state, and the tape was broken in four places. The quality of the DFDR data, with a sample rate of 1 Hz, was improved by applying several interpolation routines to the original raw data parameters for the estimation of missing or damaged parts. During the reconstruction, several repeated revisions and corrections to these data were made, based on engineering judgment, using the original raw data dump. The Flight 1862 simulation model reconstruction for the GARTEUR FMAG(16) benchmark is based on a model validation method using inverse simulation [19] (Figure 5). The DFDR pilot control inputs U_p are directly applied to the nonlinear simulation

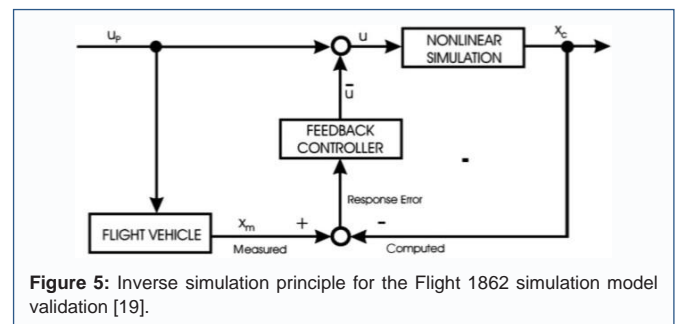
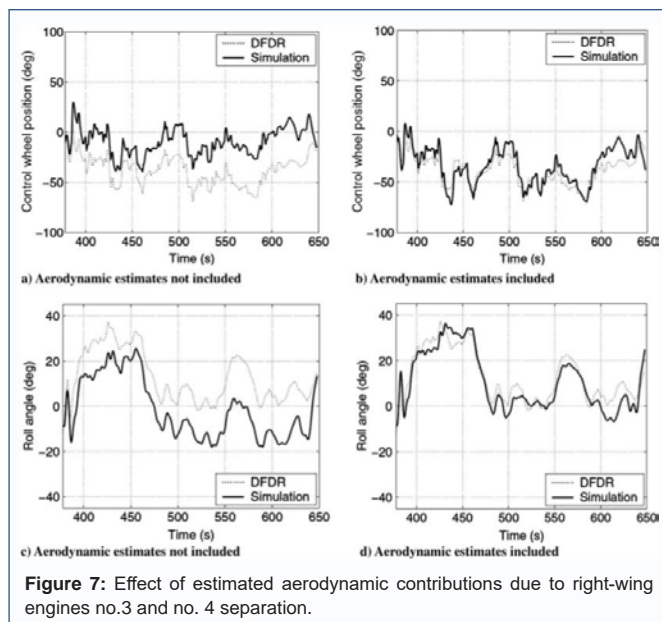
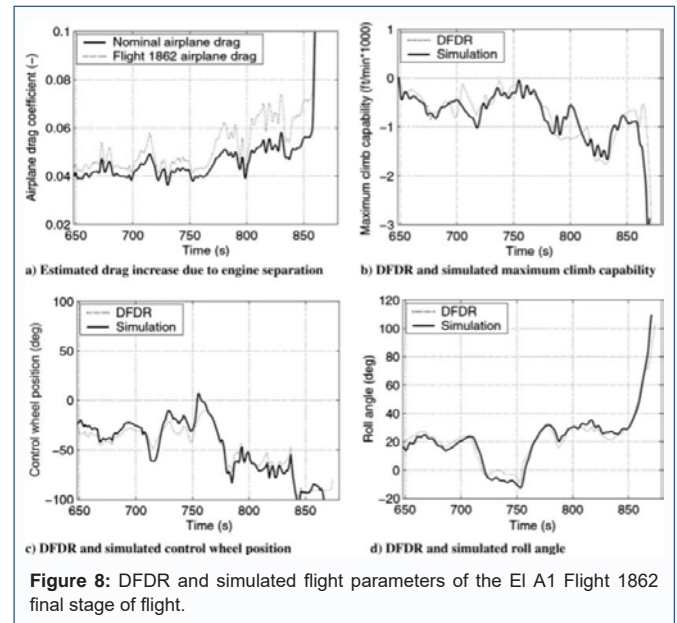
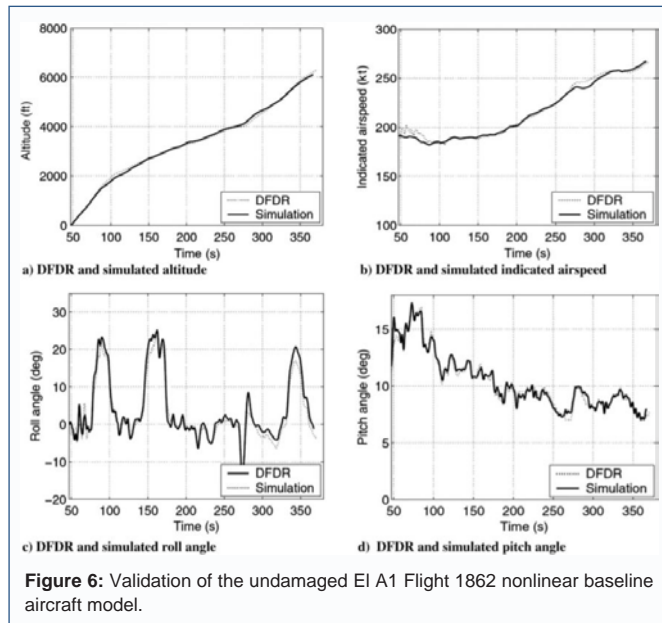


Figure 5: Inverse simulation principle for the Flight 1862 simulation model validation [19].

model of the aircraft and the flight control system. The response error of the simulation output X_c and measured DFDR data X_m are input to a feedback controller. The output of the feedback controller is a measure of the fidelity of the reconstructed model. The reconstruction method has the advantage that the combined effect of structural and flight control system failures can be visualized using the simulation inputs and outputs.

An additional advantage of the method is that the DFDR data, with a low sample rate, can be use directly to excite the simulation model and assess the proof of match. A proportional feedback controller is used to feed back the DFDR and calculated pitch and roll state error responses to obtain a reasonable match between DFDR measurements and simulation data. Initial model validation was conducted for the departure phase of the undamaged aircraft using the published Flight 1862 weight and balance configuration. This allowed a validation of the undamaged nonlinear baseline aircraft model and reconstruction methodology by means of a proof of match with the DFDR data. The additional effects due to engine separation could then be isolated and identified for the damaged aircraft in the subsequent flight phases using the model reconstruction process. The example flight parameters illustrated in Figure 6 [altitude above



mean sea level (MSL), indicated airspeed, roll angle, and pitch angle] show that the applied reconstruction methodology achieves a close match between the DFDR and undamaged baseline aircraft model before the separation of the rightwing engines at $t = 378$ s for the Flight 1862 departure phase ($t = 47$ 371s). The objective of the simulation tuning process was to closely match the Flight 1862 trends in performance and control capabilities as provided by the DFDR throughout the different flight phases. Figure 7 illustrates the effects of the estimated right-wing damage aerodynamic contributions on example simulation model inputs and outputs for the lateral control characteristics (control wheel deflection and roll angle) for the flight stage between $t = 378$ s and $t = 647$ s. It can be seen that, under the prevailing flight conditions where both rightwing engines no. 3 and no. 4 are separated, a reasonable match between the DFDR and simulated control wheel deflection and roll angle can be achieved.

Figure 8 depicts the DFDR and simulated flight parameters of the

EI A1 Flight 1862 final stage of flight up to the loss of control (inboard trailing edge flaps 1, $t = 648$ 874 s) Figure 8a shows the estimated amount of aerodynamic drag increase, due to the loss of the right-wing engines, obtained by reconstruction of the Flight 1862 DFDR aircraft performance capabilities. The figure indicates that a drag increase of about 10 percent at a low angle of attack may be expected, as compared to the unfled case.

Figure 8b shows the significant reduction of the aircraft's maximum climb capability down to approximately minus 1500-2000 ft/min , as observed on the DFDR, and can be predicted well by the reconstructed model. The reduced control authority of the damaged aircraft is insufficient to recover from the significant performance degradation using the remaining engines as shown in Figures 8c and 8d. Figure 9 presents the performance and lateral control capabilities of the reconstructed Flight 1862 accident aircraft model, after separation of both rightwing engines, as a function of thrust and aircraft weight.

Aircraft Benchmark Model

An aircraft simulation benchmark has been developed by the GARTEUR FMAG (16) research group. It is based on the reconstructed EL A1 Flight 1862 aircraft model and the purpose was to assess the novel fault-tolerant flight control techniques. The benchmark simulation environment (RECOVER) is focused on the Deft 9 University Aircraft Simulation and Analysis Tools (DASMAT). This benchmark is used as a MATLAB/SIMULINK platform for the design and integrated (real-time) of new fault-tolerant flight control techniques. The benchmark consists of a set of high-fidelity simulation and flight control design tools, including aircraft fault scenarios. It has been validated against data from DFDR of the EI A1 Flight 1862 Boeing 747-200 accident aircraft for a representative simulation of damaged aircraft handling qualities and performances. The benchmark software is equipped with several simulation and analysis tools, all centered around a generic nonlinear aircraft model for six-degree-of freedom nonlinear aircraft simulations. Figure 10 shows the benchmark functional model operating shell for open-loop nonlinear offline (interactive) simulations and software architecture.

The user options in the main menu are divided into three

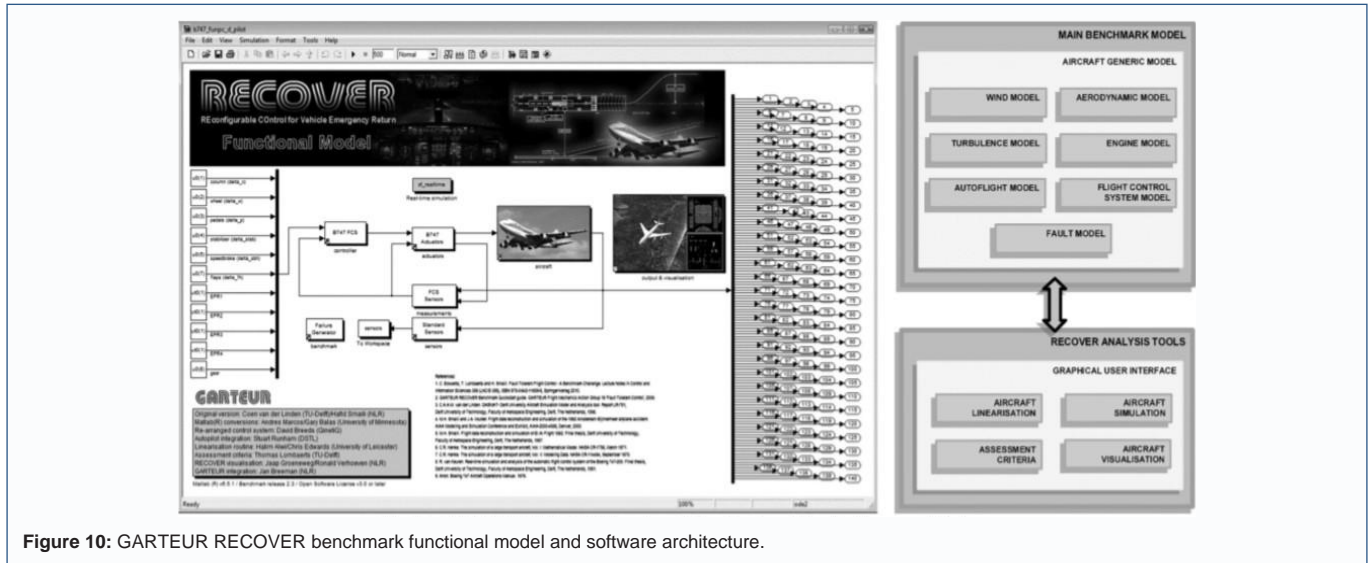


Figure 10: GARTEUR RECOVER benchmark functional model and software architecture.

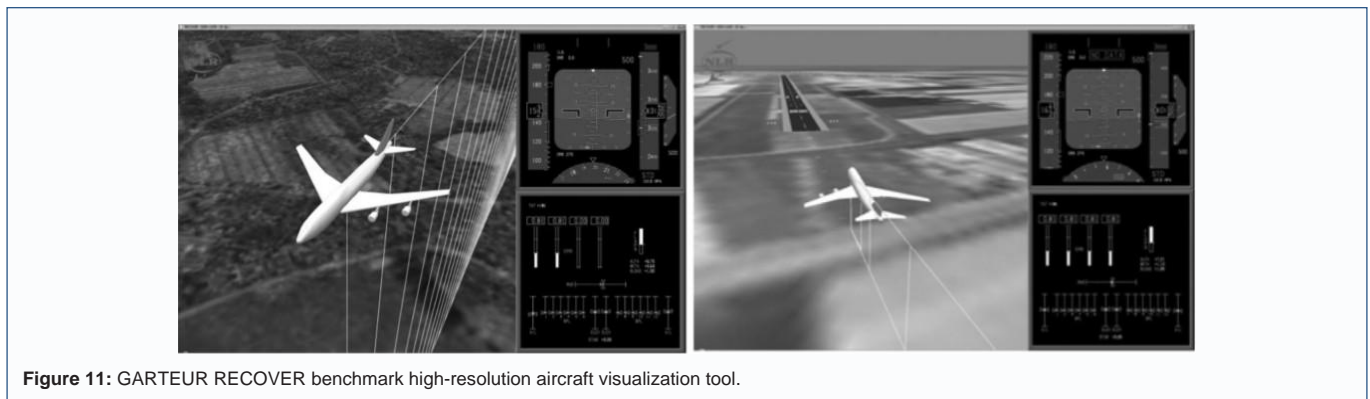


Figure 11: GARTEUR RECOVER benchmark high-resolution aircraft visualization tool.

main sections, allowing initializing the benchmark, running the simulations, and selecting the analysis tools. RECOVER benchmark include trimming and linearization for (fault-tolerant) flight control law design, nonlinear offline (interactive) simulations, simulation data analysis, and high resolution three-dimensional flight trajectory and pilot interface visualizations for interactive (real-time) simulations (Figure 11).

To control the surfaces separately, as required for the reconfigurable control algorithms, the pilot controls to actuators block is separated from the baseline aircraft model.

However, the aircraft in the stable condition at the threshold, the landing can be easily manage by the pilot.

Flight Simulator Integration and Piloted Assessment

Motivation and Goals

An online piloted moving-base simulator evaluation of intelligent flight control systems may bring out new perception into real-time performance issues, applicability in an operational environment and, if applicable, handling qualities of deferent aircraft configurations. It can be benefit for the controllers in terms of compensation for impaired aircraft control, performance improvements in failed configurations, and lowering of pilot workload. Many algorithms concerning fault-tolerant right control have been developed by the GARTEUR FM-AG(16) as depicted in Table as part of their work,

a real-time assessment and piloted evaluation were performed for several of these algorithms.

Flight Simulator Configuration

The GARTEUR FM-AG(16) piloted evaluation was performed on the SIMONA Research Simulator as shown in Figure 14. SIMONA is a six-degree-of-freedom research right simulator, with configurable right-deck instrumentation systems, a wide-view outside visual display system, hydraulic control loading, and a mo15 motion system.

Aircraft Configuration and Validation

The benchmark model and the designed fault-tolerant control algorithms is converted from Simulink to the real-time environment for piloted experiment. To assure the correct implementation of the benchmark model, several validation steps have been performed. The validation steps include proof-of-match validation and piloted check out of the baseline aircraft, control feel system, and Flight 1862 controllability and performance characteristics. The aircraft model can be own in the manual classical flight control system mode and in the manual y-by-wire mode, where flight control is performed via the subsequent FTFC module (design dependent).

Test Method

The test method of the piloted evaluation is designed to assess the FTFC failure mode accommodation capabilities in terms of aircraft upset recovery and stabilization, controllability, and pilot workload to restore handling qualities up to levels that at least allowed a

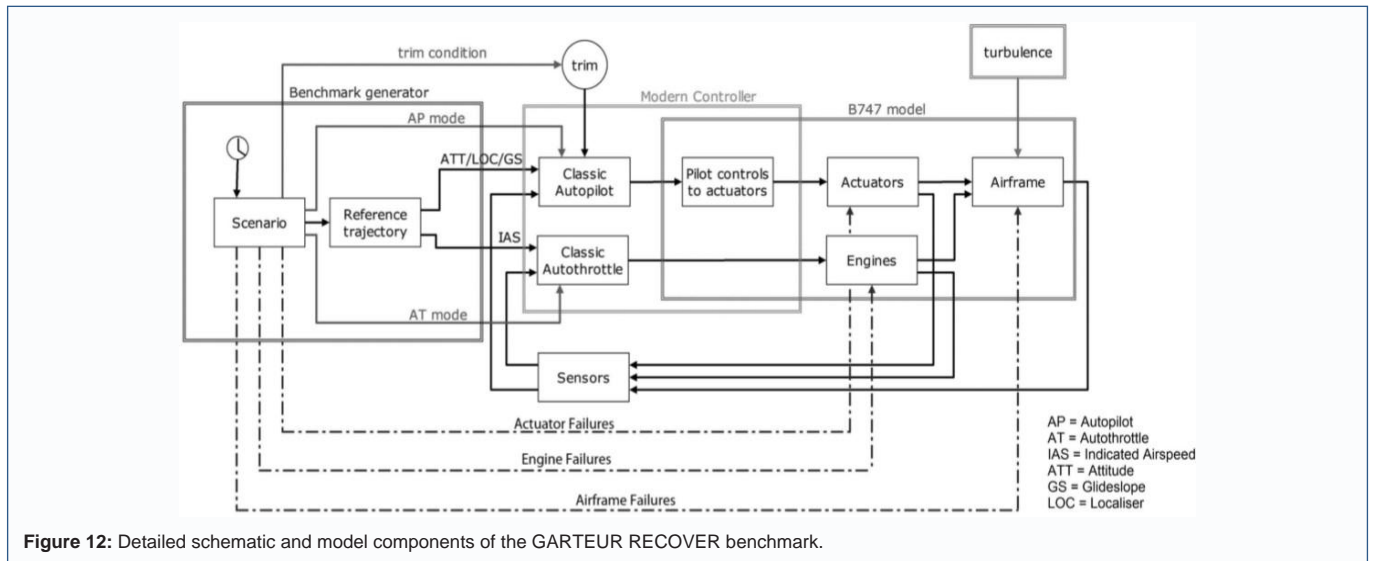


Figure 12: Detailed schematic and model components of the GARTEUR RECOVER benchmark.

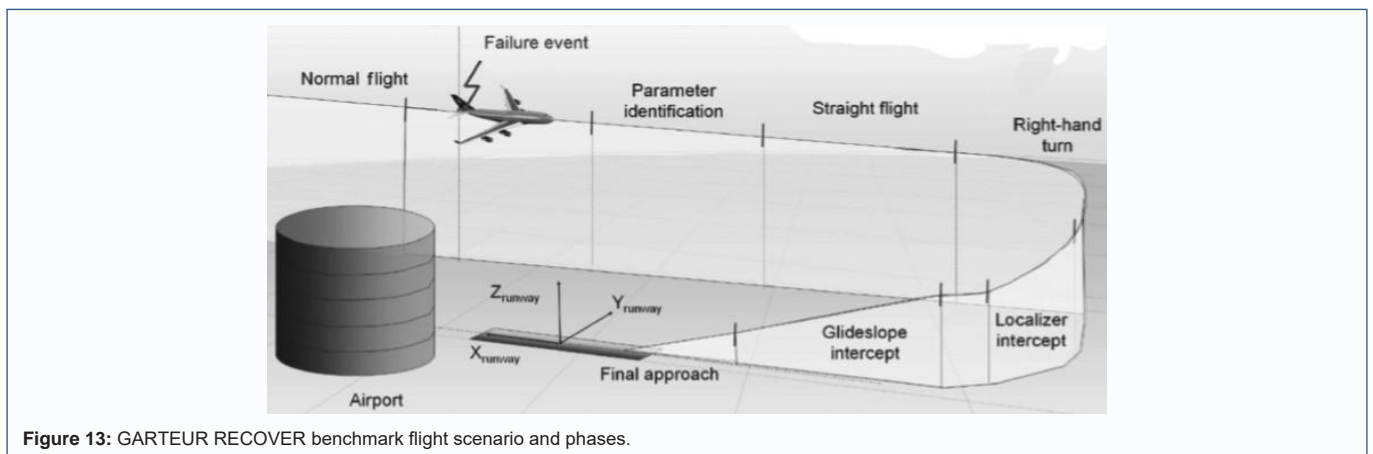


Figure 13: GARTEUR RECOVER benchmark flight scenario and phases.

No.	FTFC algorithm	Control type
0 ^a	Classic flight control system	Manual (classic)
1 ^a	Model reference adaptive sliding modes control with control allocation	Autoflight
2 ^a	Integral action control	Autoflight
3 ^a	Fault tolerant control with guaranteed nominal performance H_{∞}	Manual (classic) and altitude hold
4	Fault detection, identification, and reconfiguration system based around optimal control allocation	Manual and autoflight
5 ^a	Subspace predictive control	Autoflight
6	Real-time model identification and model predictive control	Manual (FBW)
7 ^a	Real-time model identification and nonlinear dynamic inversion	Manual (FBW)
8	Adaptive model following control	Autoflight

Table 2: GARTEUR FM-AG(16) fault-tolerant flight control algorithms.

survivable landing. The aircraft is own in both the conventional (classical) control mode and in the y-by-wire FTFC mode in order to have a good comparison. Fault detection and isolation capabilities are tested on their robustness under real-time environmental conditions, including continuous aircraft maneuvering. The FTFC modules is tested using the same flight scenario and failure modes. During each flight phase, it is dined appropriate exercises with performance criteria

to rate the handling qualities of both the undamaged and damaged aircraft. Each pilot performs one run of each configuration. And the pilots give a handling qualities rating for each flight phase using the Cooper Harper (CH) rating scale after each run. Pilot workload is obtained for each scenario phase by measuring the combined pilot control force activities for the wheel, column, and pedal.