Back to Session Subjects

On the Development of a Four-axis AFCS for the Pilot Assistance Experimental System.

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Abstract

The paper describes the Pilot Assistance development programme from the perspective of automatic flight guidance and control. The programm aims to investigate flight procedures based on advanced position sensors in combination with digital terrain databases allowing autonomous helicopter flight below air-controlled airspace. A trajectory formulation concept is presented using clothoid functions and the functionality of the core flight control system is demonstrated using ground and flight tests.

1 Introduction

In recent years due to rapid improvements of satellite-based position determination many new applications for automated flight path cotrol have appeared. GPS-based applications are common for ships, fixed wing, UAVs and other flight vehicles. However, all the above applications involve either obstacle-free operating environments, possibly with reduced safety requirements, or slower processes, where human corrective action is feasible within reasonable time. This new spectrum of operations is a long time dream of the helicopter world, where an obstacle-free environment can not be easily defined - or if it is determined it will be most probably be complemented with strict requirements on sensor accuracy and guidance algorithm performance.

To investigate the operational use of the new technologies for all-weather operations EUROCOPTER has used a variety of aircraft, notably an EC155 (“Helicoptere Tout Temps”) and a BK117 (“All-Wetter-Rettungs-Hubschrauber”) in France and Germany respectively [3],[4]. Three-dimensional navigation and flight management combining terrain databases were extensively tested to determine head-up and head-down display requirements for synthetic world representations complemented with symbology overlays for guidance purposes. A generic requirement for display information was achieved for a variety of missions. In a further project EUROCOPTER DEUTSCHLAND GmbH with the support of the German national LuFo[1] programme, devised an avionic concept combining 4-dimensional (4D) vision (the three classical spatial coordinates plus time-stamped guidance) with precision algorithms to investigate low level automatic flight. The spatial coordinates are defined using a safe corridor (“the tunnel”), basically a 3D area on the basis of Satellite-based Augmentation System (SBAS) position measurements. The current SBAS platform for the tests is the European Geostationary Navigation Overlay Service (EGNOS) for which a dedicated sensor has been used.

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[1] Luftfahrtforschungsprogramm der Deutschen Bundesregierung.

Given the desire to expand helicopter operations for night and in bad visibility conditions[2] the next sections describe all aspects of this development from the 4D requirements, the guidance and stabilisation system as well as the first flight test results achieved in 2005. Arriving to these flight results was possible combining development test benches, ground simulations as well as flight tests using a modified EC145 test aircraft. Section 2 describes the mission profile considered for this work and its implications on the system and redundancy architectures. The next important step, in section 3, is to define the set of admissible trajectory profiles (the "trajectory generator") and its formulation, which feeds the flight guidance algorithms with spatial and time coordinates to follow. Of course, such an operation in degraded environments requires a well-designed, rich in functionality Flight Control System (FCS), which optimally uses its available control surfaces as if a human pilot were flying the aircraft. This is described in section 4 alongside the ground simulations performed to verify its correct operation. In the sequel, section 5 presents the first flight results obtained in 2005 from the core AFCS system development and finally section 6 describes the future steps planned ahead to verify the suitability of such avionic concept for all weather operations.

2 Mission requirements and system architecture

It is widely accepted that the currently used flight rules (defined typically from fixed wing operations) do not take into account the specificities of helicopters. For example, Emergency Medical Services (EMS) are restricted to visual flight rules whereas a largely automated navigational and piloting help could be provided. A typical EMS scenario would require a flight between hospital with a helipad or between an accident site and a hospital, involving prepared and unprepared landings (see figure 1). The predicted path could consist of straight segments, descents in confined spaces (with normal and steep approach angles) for variety of airspeed requirements. Throughout the flight route an obstacle-free path must be defined for any automatic guidance, especialy for initial approach, take off or go-around procedures. Although the above objective increases helicopter usage to IFR-like operations below controlled airspace this is not expected to waive the necessity of having the ground in sight just before crossing a Landing Decision

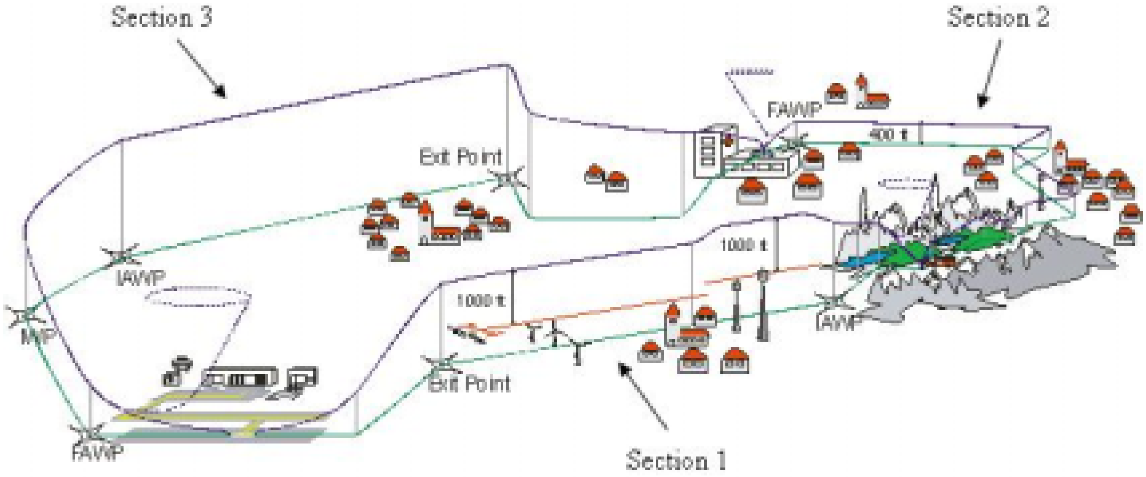

Figure 1: All weather EMS mission scenario

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[2] Currently such operations are reduced between airports along fixed airways at high altitude.

Point (LDP). If until the LDP the crew can not visually confirm obstacle-free flight path they would perform a missed approach. In addition, horizontal and vertical constraints will also depend on performance issues as well as failure events during the flight. Except the well-known optimally-chosen flight paths against digital ground maps the described mission poses additional strict reqirements for flight management and control system architectures. That implies certainly secure calculations of the flight management path, assisted by inertial and position sensors (SENS) with cross communication for monitoring and discrepancy checks. A 3-dimensional Digital Map system (DMC) with computing capabilities and guidance annunciations will be required for ensuring reliable guidance and autopilot (FCS) information flow to the crews. A candidate demonstrator cockpit concept is shown in figure 2. Here, on the right side of figure 2 synthetic vision is superimposed with appropriate flight guidance symbology. In addition display retains the flight control system modes of operation, references and heading information similarly to figure 6 shown later in section 4. The cockpit setup is complemented with a moving map for trajectory definition as well as the Eurocopter "classical" glass-cockptit Avionic Nouvelle, implemented on the left side for the co-pilot tasks.

Figure 2: Four dimensional mission annunciation

3 Trajectory formulation and guidance requirements

In this section there are two basic questions that are being addressed: firstly, how can we calculate realistic path following trajectories based on performance data and secondly what kind of flight guidance and control architecture is required to follow these trajectories ? Both these questions have been known from the nap-of-the-earth flight of the fixed wing community however, operational constraints from the helicopter world make the trajectory constraints more strict. Here, there are also two different situations. On one hand military operations which can accept higher load factors in all directions, but also more pilot workload due to the specificities of their mission. On the other hand EMS operations would probably require very smooth flight paths achievable not only with the pilot in the loop, but also by an AFCS designed for an IFR flight. Although this argument will have to be substantiated with flight data currently it has to be assumed that load factors encountered in IMC conditions, would also be required for an EMS scenario in an uncontrolled airspace like in the figure 1. Of course, exceptions will exist for emergency operations, but these would render this article too lengthly if we were to list them. For the time being it is important to describe the basic concepts of admissible trajectories in the guidance system without their detailed limitations.

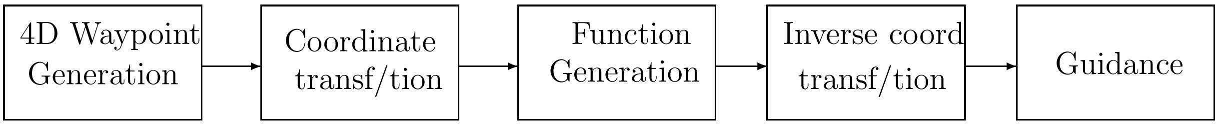

Figure 3: Trajectory generation process

Typically, a mission is designed on the basis of 4D waypoint generation in WGS84[3] coordinates (geodetic longitude λ, latitude ϕ, height h and time t). Choosing an orthogonal cartesian frame (e.g. NED) seems to be more attractive for admissible trajectory segment formulation using standard coordinate transformations (see figure 3). Once in this form one defines a set of admissible functions to parametrise the 4D reference trajectory and feed with the resulting reference the guidance loops. For these functions to be defined one needs to firsly define basis functions $x(l), y(l), z(l)$ and treir derivatives in space l

$$x^{'}(l) = cosX(l)cos\Gamma(l), \quad y^{'}(l) = sinX(l)cos\Gamma(l), \quad z^{'} = -sin\Gamma(l), \tag{1}$$

where $X(l), \Gamma(l)$ represent the flight path azimuth and angle of climb such that $x'(l)^2 + y'(l)^2 + z'(l)^2 = 1$ and the length of a curve is given by

$$L = \int_0^l \sqrt{x'(l)^2 + y'(l)^2 + z'(l)^2 dl} \tag{2}$$

Therefore, choosing appropriate quantities $X(l), \Gamma(l)$ using equations 1 and 2 it is possible to estimate the travelled distance for a variety of flight segments. As an example, for a steady turn in the horizontal plane with radius $Rcos\gamma_0$ and constant climb/descent (where γ_0 the flight path inclination angle), setting $X(l) = X_0 + \frac{l}{R}$, $\Gamma(l) = \Gamma_0$ following substitutions to equations 1 and 2 and integration one obtaines

$$x(l) = x_0 - RsinX_0cos\Gamma_0 + Rsin(X_0 + \frac{l}{R})cos\Gamma_0 \tag{3}$$

$$y(l) = y_0 + RcosX_0cos\Gamma_0 - Rcos(X_0 + \frac{l}{R})cos\Gamma_0 \tag{4}$$

$$z(l) = z_0 - sin\Gamma_0 l \tag{5}$$

In a similar manner it is possible to characterise a straight segment or a turn and the remaining issue is to integrate these two elementary parts into smooth transitions. Therefore, it is necessary to define an additional segment with a curvature from zero to a desired value depending on the distance travelled. This is performed using the known clothoid geometrical properties of the Fresnel integrals on cartesian coordinates [1], [2]:

$$\int_0^l cos\frac{l^2}{2A^2}dl, \quad \int_0^l sin\frac{l^2}{2A^2}dl \tag{6}$$

where l is the covered distance along the curve from an origin and A a scaling parameter. Although equations 6 have no deterministic closed form solution it is possible to approximate them by Taylor-McLaurin series with adequate accuracy for the corresponding calculations. Therefore, folowing substitutions and integrations the solutions can take the form of

$$\sum_{n=0}^{\infty}(-1)^n \frac{l^{(4n+1)}}{(2A^2)^{2n} + (4n+1)(2n)!} \tag{7}$$

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[3] World Geodetic System 1984

$$\sum_{n=0}^{\infty}(-1)^{n+turn}\frac{l^{(4n+3)}}{(2A^2)^{2n+1}+(4n+3)(2n+1)!} \tag{8}$$

where $turn$ takes the values of $0, 1$ for a right or a left turn respectively. Figure 4 shows an example of a clothoid function starting from the origin in the positive and negative directions with $A = 1$.

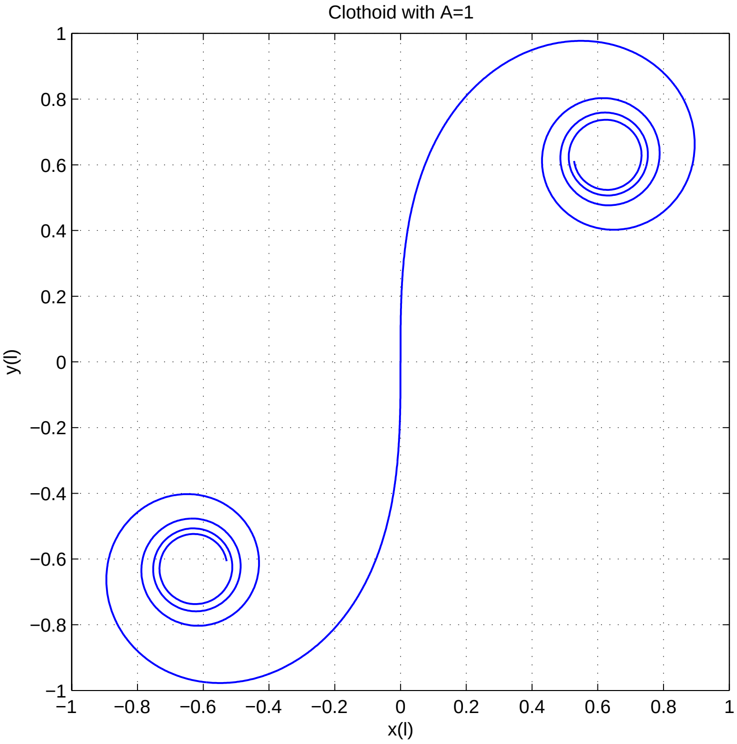

Figure 4: Clothoid functions as transition geometry between flight segments

Once the geometrical properties of the clothoid were defined the transition between segments can easily be defined. For example, a transition to turn from a straight segment can be expressed with equations 1 introducing a flight path angle

$$X = \frac{l^2}{2A^2} \tag{9}$$

and using the approximate solution of equations 7 and 8 to obtain

$$x(l) = x_0 + cos\Gamma_0 \sum_{n=0}^{\infty}(-1)^n\frac{l^{4n+1}}{(2A^2)^{2n}(4n+1)(2n)!} \tag{10}$$

$$y(l) = y_0 + cos\Gamma_0 \sum_{n=0}^{\infty}(-1)^{n+turn}\frac{l^{4n+3}}{(2A^2)^{2n+1}(4n+3)(2n+1)!} \tag{11}$$

with $turn = 0, 1$ as mentioned earlier. Note that in expressions 10 and 11 the solution would have a different form if we had assumed an initial azimuth angle X_0 in equation 9, but this was omitted for simplicity.

The example above just demonstrates the principles of using variable curvature functions to define smooth transitions between flight segments. Similarly, one can define transitions to-and-from segments not only in the horizontal but also in the vertical planes. It is also possible to make the curve parameter l time-dependant defining speed and acceleration terms, however, its formulation and implementation is outside of the scope of this paper.

Having defined the trajectory the guidance controller can be implemented in a variety of ways, from classical track error minimisation to any advanced on-line optimisation generating optimal references. A classical method can include a PI (proportinal/integral) scheme with the ability to regulate in a time horizon ahead of the aircraft position taking into account the delay imposed by the aircraft response in each axis. Another method also investigated uses predicting control theory which naturally incorporate time constrains with nonlinear requirements for an optimal reference tracking the clothoid trajectory. Whatever method is introduced hard constraints must be implemented and if violated from the trajectory generation loop must be indicated to the crew for corrective action. Here, the less corrections the pilot is required to make the higher the confidence on the safety and the acceptance of the crews to novel guidance principles.

Once the guidance outputs are defined one ends up with a set of objectives in four dimensions, which are to be executed by the flight control system considering operational constraints, failures, missed approaches etc. It is obvious that height, airspeed and directional commands must be optimally executed between the available control effectors of a helicopter.

4 Automatic flight control system

A flight control system capable of executing guidance commands must only be of a fail-safe architecture combining dual processing units which acquire helicopter angles, rates, radio and height sensors, calculate the control laws and transmit them to the actuators. These units (typically known as autopilots) operate in a duplex manner in a hot-spare principle, where their respective CPUs are cross monitoring each other for discrepancies, failures and malfunctions in real time. Typically, “the master” processing unit is able to control the actuators and only after its failure the second autopilot can take over the aircraft control without loss of functionality or pilot interventions. A similar 3 axis (pitch, roll, yaw) autopilot was described in [5], however, in a fully automated 4-dimensional flight path control one must optimally make use of control allocation algorithms for height, airspeed and directional commands optimisation as mentioned earlier. In this paper this 4-dimensional capability is realised via 6 Smart Electromechanical Acuators (SEMAs), which are distributed as follows: two for each pitch and roll axis and one for directional and heave directions respectively. (P,R,Y & C in figure 5) with a set of relays dictating which FCC commands the aircraft actuators. The additional heave actuator receives commands via an ARINC line from the two autopilots, handling high frequency requirements. Figure 5 shows in a simplified diagram the described actuator architecture.

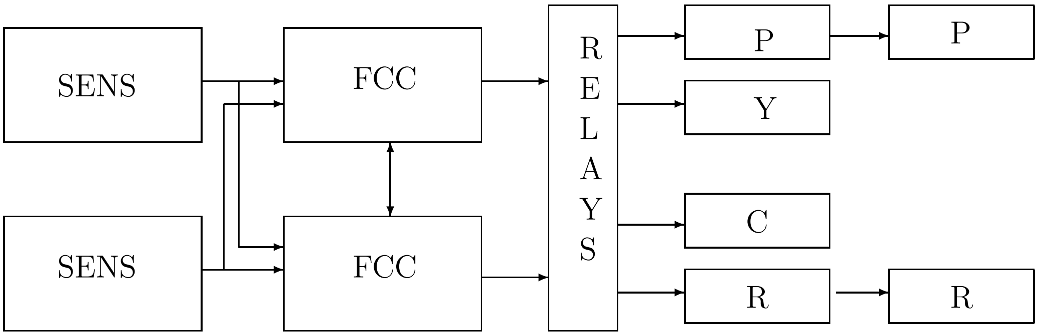

Figure 5: Duplex autopilot configuration for IFR operations

In addition, parallel actuators are integrated in each of the controlled axis for recentring the series actuators and trimming. In the collective axis the parallel actuation provides essentially power adjustments according to the flight state requirements. The total sensor-autopilot-actuator architecture is ideal for guaranteeing long time attitude retention for different flight regimes - the crew does not even have to adjust power requirements for large trim changes. This is important for several manoeuvres especially for steep approaches in IMC conditions where the crew must concentrate to the predicted and displayed trajectories. The capabilites of low speed automatic flight are enlarged: it is possible to automatically accelerate from low speed in a “trans-up” fashion if the crew is not able to visually confirm a landing site. In brief, the collective logic and control laws provide the following automatic functions:

- Steep approaches.
- Compensate for power requirements, throught the flight envelope. This is enabled with 100authority using series & and parallel actuation in a complementary scheme.
- Four-axes decoupling.
- Acceleration/deceleration from any flight state to cuise/hover.
- Hover and height position hold with ability for fly-through functions, reference changes, cross wind compensation.
- Hover follow up functions, where the centre-stick inceptor follows the natural trim requirements without trim release force allevations. The pilot in this way can arrive quicker to the centre stick inceptor position required to maintain the desired hover trim state.
- Optimised use of control redundancy between pitch and heave axes for best climb performance and fuel consumption usage. In addition, simultaneous mode usage such as Altitude acquire/altitude hold (ALTA/ALT), Indicate aispeed (IAS) and heading (HDG) are optimally combined to provide pilot workload alleviation.
- Cruise radar height mode.

In addition to the above list of points a number of classical protection functions have been implemented allowing certain degree of carefree handling to the piloting task. Here, it is important to note that since the pilot can override all AFCS functions he can intentionally cause the aircraft to exceed its limits. In a typical operation however, the AFCS will provide the required protection ensuring safe flight. For example, if the crew unintentionally exceeds V_{ne} (Velocity Never Exceed) just letting the controls would result into returning to the defined safe airspeed limits with a simultaneous annunciation about this exceedance. If equally the airspeed from a cruise state of 65kts drops below a predefined low limit (e.g. 60kts) as long as the power required to re-gain speed is adequate the AFCS control allocation mechanisms will drive the airsped via the pitch axis back to its previous reference. Equally important is the automatic level off when nearing the ground. In case of a descent, within an (unguided) automatic mode, the aircraft aligns its altitude to an optimised safe value, which is estimated on the basis of radar height sensor. The other features within the current PILAS AFCS are “standard” autopilot functions such as VOR long range navigation, ILS and glideslope approaches as well as go-around for missed approaches at cruise speeds.

To test and optimise envelope protections and autopilot logics a high-fidelity nonlinear simulation was build and interconnected with the real autopilot hardware. The flight dynamics model was compared and optimised with flight data, the real avionic housing of the aircraft was used in the simulation to host the on-board computers, which via a set of electronic interfaces

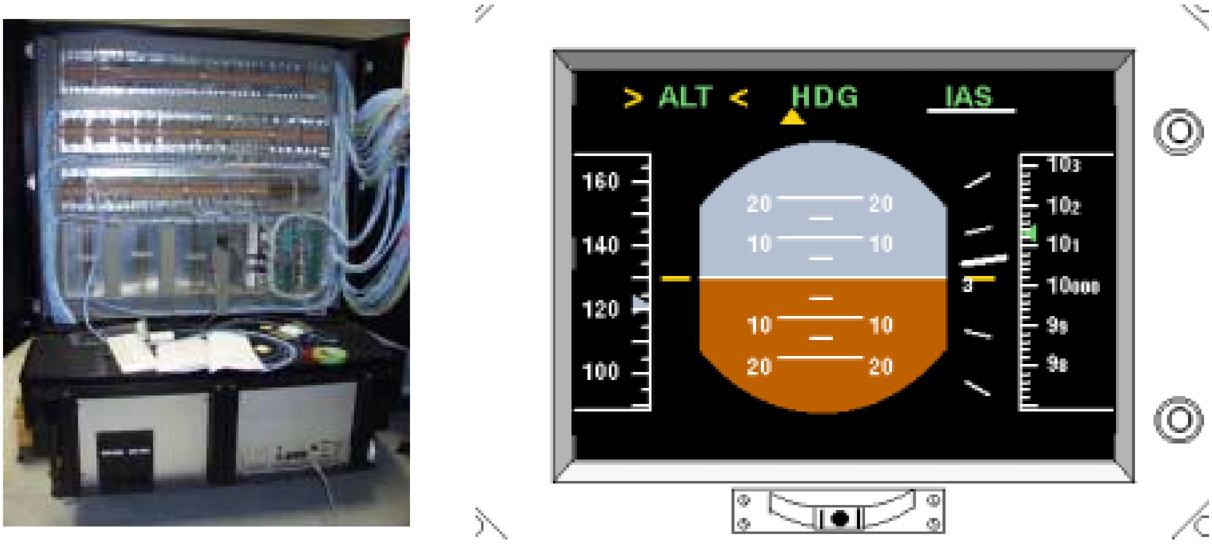

Figure 6: Hardware-in-the-loop rig (left) with integrated primary flight display (right)

drive the flight dynamics model. Given the fact that the software-hardware interaction consumed a large time of this new experimental project it was deemed necessary to complement the simulation with the real helicopter hardware units. Therefore, the real autopilot hardware was wrapped around via real wiring, aircraft series relays and switching logic ensures almost perfect match between flight and ground-based closed loop behaviour. The model was also coupled with navigational databases with VOR, ILS, GS signals, visuals, harware mode engagement panels, pilot inceptors and parallel actuators in order to provide as realistic as possible environment for development reasons. Figure 6 shows the structure of the resulting rig which allows any possile hardware failure to be re-created and the corresponding software-hardware interaction to be checked. At any point “to” or “from” the autopilot hardware the engineers could interrupt all the wirings simulating single and multiple failure cases. On the right side of figure 6 the “classical” primary flight display of the EC145 aircraft was complemented with an additional display information column for the collective axis (ALT). In the same picture one can see the available annunciations in this configuration for four-axis operations: the left side relates to the collective axis engaged modes (ALTitude hold in this case), the middle column corresponds to roll/yaw piloting mode (heading mode shown) and on the right column shows which modes are realised via the pitch axis (Indicated airspeed). The white underlying of a mode implies change of reference via beep actions (IAS), the yellow triange aroung HDG is an advisory to the pilot to recenter the series actuation by pressing the left pedal and the amber shevrons around ALT indicate that the helicopter state is too far away from the references given by the crew - usually via inadvertent overrides. In total the display information is coherent with the traditional Eurocopter Avionic Nouvelle family and minimum pilot effort is required to adapt to the four-axis flying information from the currently certified 3-axis EC145 helicopter.

Figure 7 shows a typical usage of this hardware-in-the-loop environment. An engine failure was simulated and its subsequent recovery actions provided by the control allocation algorithms are analysed. The aircraft initially is at a state of Indicated Airspeed and Altitude hold (IAS, ALT) at $120kt$, $3500ft$ realised by the pitch and collective axes respectively (subfigures 7_21 and 7_22). Here, the notation “7_22” means row 2 column 2 of the figure number. $370sec$ into the “flight” engine 2 fails, indicated by the drop of the the corresponding torque in subfigure 7_11, while the torque of engine 1 exceeds the MCP (Maximum Continuous Power) limit. Following failure recognition logic the control allocation trades off between altitude and airspeed modes and eventually reduces the airspeed to approximately $103kt$ in order to respect the MCP for the rest of the flight. Subfigure 7_12 shows the pilot inceptors being repositioned by the AFCS only to sustain the new flight condition without any pilot intervention. Numerous tests and failure simulations were performed before flight testing the core control system. The tests proved instrumental to coding and logic failures however, the acceptability of such functionality can only be judged on the basis of flight tests.

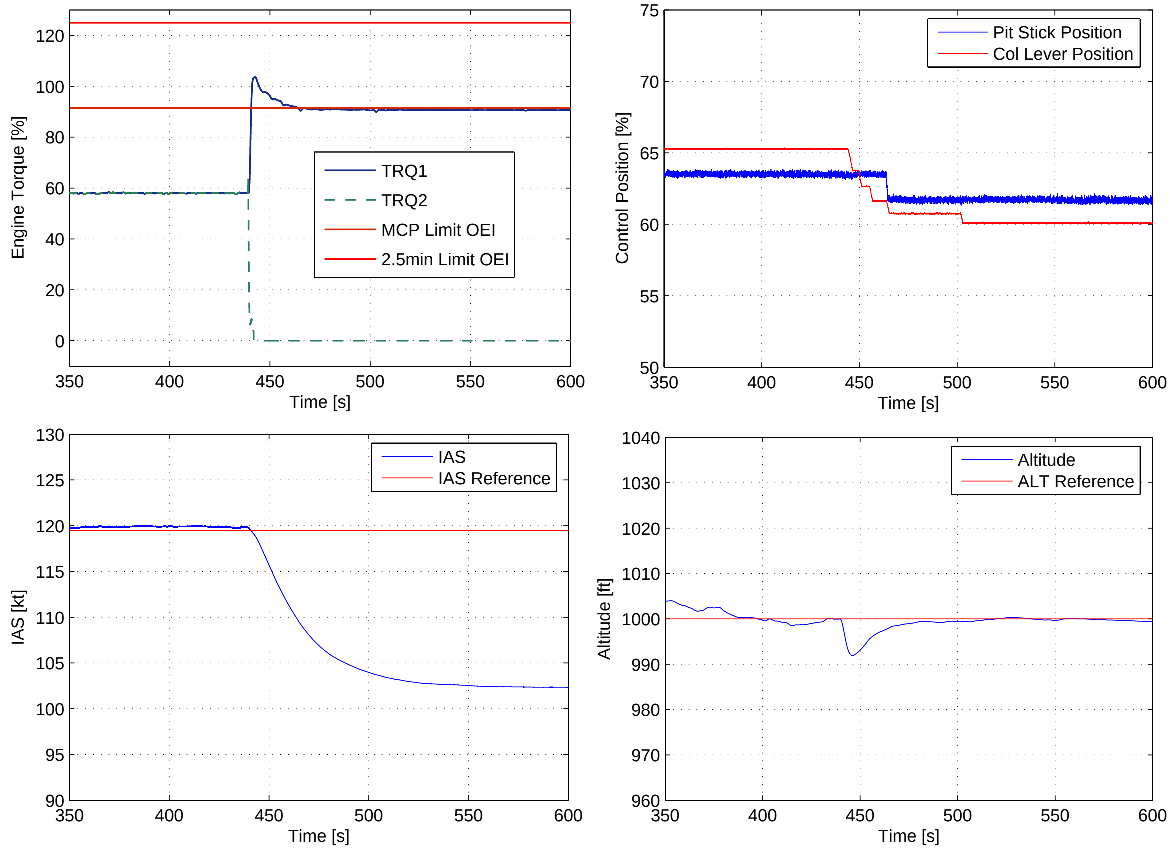

Figure 7: Engine failure recovery at 120kt indicated airspeed

5 Flight testing

For the PILAS system 3 flight test periods were defined. The first one, for which data will be presented concerns the core four-axis AFCS system around which guidance loops and flight management commands are integrated. The second test phase is planned for the summer of 2006 and includes failures, steep approaches and automatic hover investigations using precision position sensors according to the mission scenario of section 2. Finally, in the end of the 2006 the total coupled guidance, trajectory generation, guidance annunciation and flight control system are to be tested using the proposed limitations of landing and take off procedures.

As in every development the flight test started from the initial inner loops measuring the torque response to a variety collective inputs from the autopilot. This was necessary to identify proper limiting functions and smooth transitions from one torque value to another. Note that although torque is mentioned as the main concern in this paper the gas generator outlet speed needs also to be taken into account since at high altitudes it is the dimensioning parameter in the heave axis. Except the typical four-axis cross couplings that were neccessary to be reviewed, the addition of the collective fast electromechanical actuator was readily achieved and efforts were concentrated on the collective inceptor itself. This inceptor was driven by a parallel actuator of a friction type, the positioning and the friction levels of which seem to be adequate for the flight tasks. In all flight manoeuvres the collective limiting and behaviour was smooth as predicted and it did not cause any concern to the crew.

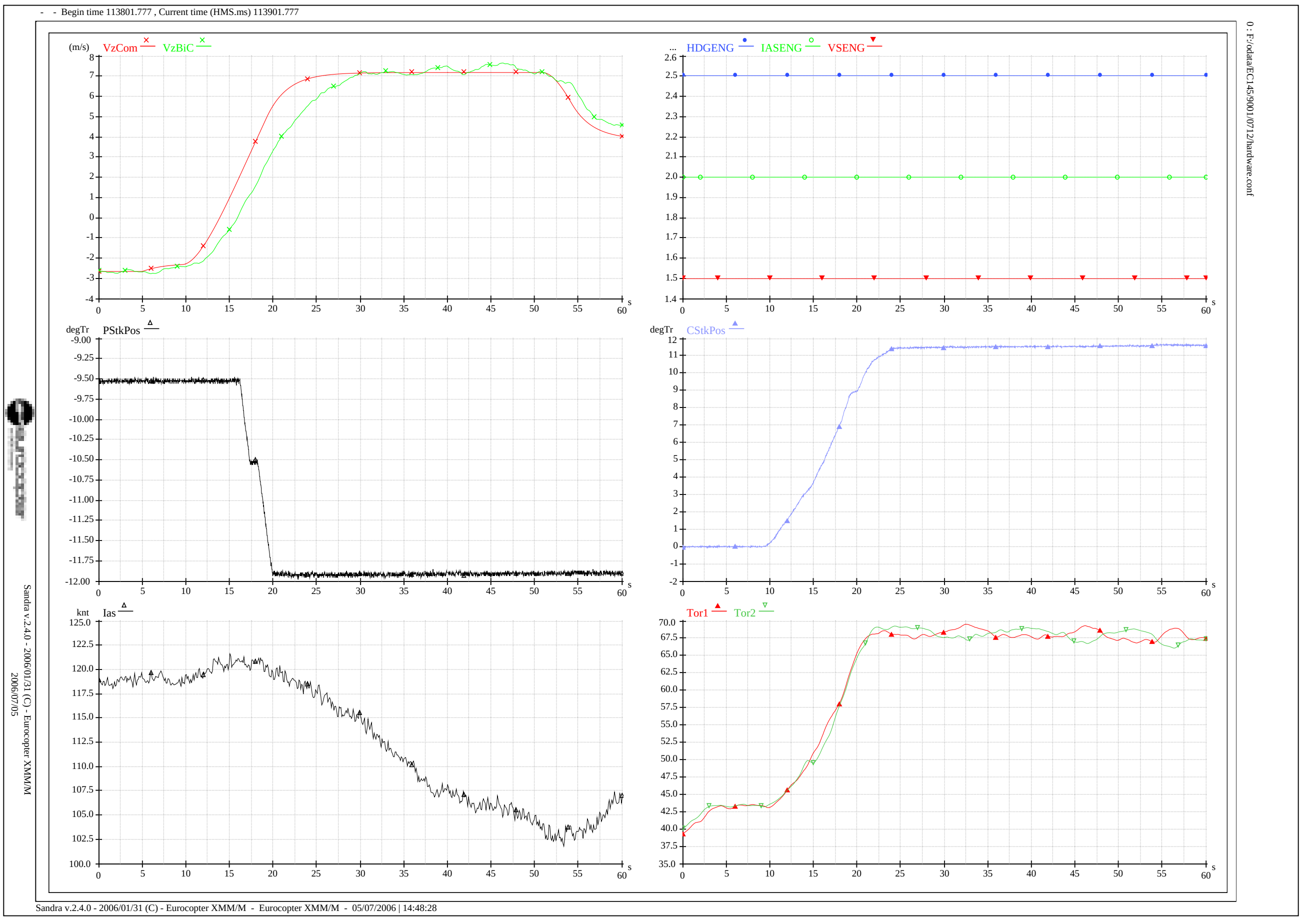

Figure 8: Control allocation trade off between collective and pitch axes in climb

Figure 8 shows a typical four-axis verical speed change performed in heading, indicated airspeed and vertical speed hold modes (indicated by nonzero values in subfigure 8_12). The rest of the signals on figure 8 are as follows: subfigure 8_11 shows the commanded and the achieved vertical speeds (red and green lines respectively), subfigures 8_21 and 8_22 the pitch and collective inceptors and finally subfigures 8_31 and 8_32 present the indicated airspeed and the torque measurements of the two engines. It is evident that while the aircraft is descending with approximately $-2.5 m/sec$ at $120 kts$ IAS, a large increase of vertical speed requires the trade off of the indicated airspeed requirement in order to allow the aircraft to climb to the desired altitude. The inceptors are being driven by the parallel actuators to their natural trim positions to sustain the new flight state. Like in the classical Eurocopter Avionic Nouvelle family of cockpits pilot overrides, reference changes, beep actions were also implemented as shown in figure 6. Extensive flight tests were performed using this four-axis configuration and crews were very positive about the system's usage to perform hands-off approaches. Detailed annunciation, information databases, trajectory choice and optimisation against performance data are also expected to change the perception of the pilot when navigating at low altitudes. However, the paper would be too long to describe the curently performed ground and flight experiments of the PILAS experimental programme.

6 Conclusions and future steps of this work

Following the first steps of development, integration and flight testing several messages are being emitted by this work. Firstly, the maturity of a fully automated flight below air-controlled airspace reaches good levels in order to be allowed for normal operations. The technology is available, but it is important to integrate it in an optimised manner ensuring safety. The basic formulation elements of a particular trajectory parametrisation were given as a specific class of functions, which in the right combination, can characterise a complete flight plan with flexibility and minor conservatism. The core AFCS systems must allow not only hands-off standard operations, but also be able to approach at steep angles taking into account engine failure and peformance limitations. The next steps of this work require flight testing of the complete system and tailoring to crew operations such as trajectory interruptions or operational limits at the terminal phase of a guided steep descent followed by missed approaches and emergency procedures.

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