RECONFIGURABLE FLIGHT CONTROL OF A HIGH INCIDENCE RESEARCH MODEL USING PREDICTIVE CONTROL

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Abstract. This paper describes a scheme for fault-tolerant control of an aircraft with a high angle of incidence. The scheme is an example of a generic scheme proposed in (Maciejowski, 1997), adapted to the particular needs of this application. It combines the use of a high-fidelity model of the aircraft with model predictive control, and assumes the availability of information about the fault which has occurred from an FDI system. This paper examines the performance of the proposed fault-tolerant scheme in the presence of severe failures of control surfaces and of the aircraft structure. It contains details of a modelling methodology which enables updating of the model with failure information, and of a methodology for on-line re-linearisation. The modelling methodology follows the introduced in (Huzmezan and Maciejowski, 1998).

Keywords. Reconfigurable Flight Control, Predictive Control, Optimisation, Fault Tolerant Control

1. INTRODUCTION

This paper is concerned with fault tolerant control. In previous work (Huzmezan and Maciejowski, 1998; Maciejowski, 1997) we addressed structural or actuator failures. In this paper we address the simultaneous occurrence of both phenomena.

Our research is based on a strong hypothesis, that accurate Fault Detection and Isolation (FDI) is performed by a dedicated system outside of the control algorithm.

In this paper we describe a feasible way of providing control fault tolerance for the simplified longitudinal channel of a wind tunnel model of the High Incidence Research Model (HIRM). We owe the development of the model to the authors of (Magni *et al.*, 1997; Willcox, 1997). This model has redundant motivators, taileron and the canard, in the longitudinal channel. The high-fidelity model developed in the case of this aircraft is regarded as being enough accurate to reflect a wide class of failures detected and isolated by the FDI system.

Our solution relies on the combination of high fidelity modelling, on-line linearisation tools and predictive control (Maciejowski, 1997). The solution requires that the high-fidelity model is available for on-board use and the on-line solution of optimisation problems. The overall scheme is complicated, but we consider that it has good potential for providing fault-tolerance. This is what we try to show in this paper.

To allow a real time, practical, implementation several simplifications were made in the following ways:

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- The way contributions of various aerodynamic surfaces enter the nonlinear model.
- The way a linear internal model is computed for the predictable controller.
- The choices of certain tuning parameters.

This paper briefly surveys the modelling of the aircraft followed by an exposition of the methods employed to produce a linearised model on-line. The third section describes the overall controller structure, and the design cycle. The fourth section presents simulations results with the aircraft being subjected to several failure scenarios.

All the simulation results presented were produced using software which combined the $MBPC$ Development Space (Huzmezan and Maciejowski, 1997), the public domain Generic Rigid Body Simulation (GRIBS) Simulink files (King, 1995), and the aerodynamics and engines model of the wind tunnel model (Magni *et al.*, 1997; Willcox, 1997).

2. MODELLING THE AIRCRAFT

2.1 *HIRM nonlinear model dynamics*

In this paper we restrict our attention to the longitudinal channel of the High Incidence Research Model. We can assume that the side slip angle ant the roll and yaw rates, are zero. Due to space limitations, a detailed analysis of the uncertainty contained in the aerodynamic coefficients is not addressed even though the design provides the requested degree of robustness in face of such mismodeling problems.

The model is based on the following equations of motion:

$$
\begin{aligned}
\dot{\gamma} &= -\left(\frac{g}{V}\right) cos(\gamma) + \left(\frac{L}{mV}\right) + \left(\frac{F}{mV}\right) sin(\alpha) \\
\dot{\alpha} &= q - \dot{\gamma} \\
\dot{q} &= M\left(\frac{\bar{c}}{J_y}\right) \\
\dot{V} &= -gsin(\gamma) - \left(\frac{D}{m}\right) + \left(\frac{F}{m}\right) \\
\dot{H} &= Vsin(\gamma)
\end{aligned}
$$

In these equations γ, α, q, V, H denote the vertical flight path angle, angle of attack, pitch rate, airspeed, and altitude, respectively. The variables m, $\bar{c}$, J_y are constants denoting, respectively, the aircraft mass, the reference mean aerodynamic chord, and pitch moment of inertia.

The expressions of the aerodynamic drag (D), lift (L) and pitch moment (M) expressed in body axis are:

$$
\begin{aligned}
D &= \bar{q}S\left[C_{X_{\delta_{TS}}}(\alpha,\delta_{TS}) + C_{X_{\delta_{CS}}}(\alpha,\delta_{TS})\delta_{CS}\right] \\
L &= \bar{q}S\Big[C_{Z_{\delta_{TS}}}(\alpha,\delta_{TS}) + C_{Z_{\delta_{CS}}}(\alpha,\delta_{TS})\delta_{CS}+ \\
&\quad + C_{Z_q}(\alpha,\delta_{CS})\frac{q\bar{c}}{2V}\Big] \\
M &= \bar{q}S\bar{c}\Big[C_{M_{\delta_{TS}}}(\alpha,\delta_{TS}) + C_{M_{\delta_{CS}}}(\alpha,\delta_{TS})\delta_{CS}+ \\
&\quad + C_{M_q}(\alpha,\delta_{CS})\frac{q\bar{c}}{2V} - Z_{ATP}F\Big]
\end{aligned}
$$

where $\bar{q} = \frac{1}{2}\rho(H)V^2$ is the dynamic pressure and $\rho(H)$ the air density which varies as a function of altitude.

In the above equations the meaning of $F, \delta_{TS}, \delta_{CS}$ is thrust vector, symmetrical taileron deflection, and symmetrical canard deflection, respectively.

The non dimensional coefficients in these equations

$C_{X_{\delta_{TS}}}(\alpha,\delta_{TS})$, $C_{X_{\delta_{CS}}}(\alpha,\delta_{CS})$, $C_{Z_{\delta_{TS}}}(\alpha,\delta_{TS})$, $C_{Z_{\delta_{CS}}}(\alpha,\delta_{CS})$, $C_{Z_q}(\alpha,\delta_{CS})$, $C_{M_{\delta_{TS}}}(\alpha,\delta_{TS})$, $C_{M_{\delta_{CS}}}(\alpha,\delta_{CS})$, $C_{M_q}(\alpha,\delta_{CS})$ are given in look-up tables obtained as a result of wind tunnel tests (Magni *et al.*, 1997; Willcox, 1997). In the high fidelity model their values are computed by linearly interpolating between the values stored as functions of the variable α and the corresponding surface deflection.

The way the aerodynamics forces together with the engine thrust act upon the 6-DOF nonlinear simulation model is defined based on wind tunnel data and simple first order actuator models which include as well delays. At the moment the model is programmed in C using the Matlab Simulink S-function template and run on a SPARCstation 20 as compiled code.

2.2 *On-line point-wise linearisation*

We propose to obtain on-line linearisation of the system by using Taylor series to derive the analytical expressions for the linear equations. This is done around the current input and state pair, which are not, in general, equilibrium points (that is, the linearisation is not performed about a “trimmed” condition of the aircraft). The values of the derivatives of the aerodynamic coefficients are stored in look-up tables.

As an example, we show here the expression for $\Delta V = V - V_c$, where V is the total airspeed and

V_c is the current airspeed value at which the linearisation is performed:

$$\Delta V = -g cos(\gamma_c)(\gamma - \gamma_c) + \frac{1}{m}(F - F_c) - \\ -\frac{\bar{q}(H)S}{m}\Bigg[\Bigg(\Bigg(\frac{\partial C_{X_{\delta_{TS}}}(\alpha,\delta_{TS})}{\partial\alpha}\Bigg)_{(\alpha_c,\delta_{TS_c})}(\alpha-\alpha_c)+ \\ + \Bigg(\frac{\partial C_{X_{\delta_{TS}}}(\alpha,\delta_{TS})}{\partial\delta_{TS}}\Bigg)_{(\alpha_c,\delta_{TS_c})}(\delta_{TS}-\delta_{TS_c})\Bigg) + \\ \Bigg(\Bigg(\frac{\partial C_{X_{\delta_{CS}}}(\alpha,\delta_{TS})}{\partial\alpha}\Bigg)_{(\alpha_c,\delta_{TS_c})}\delta_{CS_c}(\alpha-\alpha_c) + \\ + \Bigg(\frac{\partial C_{X_{\delta_{CS}}}(\alpha,\delta_{TS})}{\partial\delta_{TS}}\Bigg)_{(\alpha_c,\delta_{TS_c})}\delta_{CS_c}(\delta_{TS}-\delta_{TS_c}) + \\ + C_{X_{\delta_{CS}}}(\alpha_c,\delta_{TS_c})(\delta_{CS}-\delta_{CS_c})\Bigg)\Bigg]$$

where the subscript c denotes the current value of a variable.

This procedure allows linearised models to be obtained quickly enough for real-time use. Of course it assumes that the FDI system can update the look-up tables quickly enough.

For the simulations shown in Section 4 we have employed numerical linearisation instead (the Simulink function linmod), for convenience. In principle this is giving the same linearised model.

3. SCHEDULING AND RECONFIGURATION USING PREDICTIVE CONTROL

3.1 *Fundamentals of predictive control*

The defining feature of Model Based Predictive Control ($MBPC$) is the repeated optimisation of a performance objective over a prediction horizon (N_2). Given a set-point, a reference $r(k+l)$ is produced and used within the cost function (1). Manipulating the control variable $u(k+l)$, over the control horizon (N_u), the algorithm drives the predicted output $\tilde{y}(k+l)$, over the prediction horizon, towards the reference. The future control movement over the control horizon (N_u) is determined by minimising the cost function:

$$J(k) = \sum_{l=N_1}^{N_2} \|(\tilde{y}(k+l) - r(k+l)\|^2_{Q(l)} + \\ + \sum_{l=0}^{N_u-1} \|\Delta u(k+l)\|^2_{R(l)} \tag{1}$$

subject to constraints on:

- the inputs levels: $u_l(l) \leq u(l) \leq u_u(l)$ where $k \leq l \leq k + N_u - 1$
- the input rates of change: $\Delta u_l(l) \leq \Delta u(l) \leq \Delta u_u(l)$ where $k \leq l \leq k + N_u - 1$
- the output (and state) levels: $y_l(l) \leq \tilde{y}(l) \leq y_u(l)$ where $k + N_1 \leq l \leq k + N_2$

$Q(l)$ and $R(l)$ are weights independent of time k and the norm $\|.\|_Q$ is defined as $\|\alpha\|^2_Q = \alpha^T Q \alpha$. It is assumed that $\Delta u(l) = 0$ for $l \geq k + N_u$. This optimisation is a quadratic program (QP) which is solved using a standard algorithm. Only the first command increment $\Delta u(k)$ is implemented, and the optimisation is re-solved at each step.

The general structure of $MBPC$ schemes is the following:

Optimiser computes the future manipulated variable moves. Constraints reflect input (actuator) and output (flight envelope) limitations.

Predictor employs the internal model and the measurement or estimate of the current state to provide the optimiser with predicted values of states and outputs.

Internal model represents the plant. In this paper we use a state-space linear time invariant model for the plant. This is a natural choice for flight control.

3.2 *A strategy for control reconfiguration*

The four system components: High fidelity model, Fault Detection and Isolation (FDI), model approximation/simplification and constrained Model Based Predictive Control ($MBPC$) shown in Figure 1, work together as follows in order to provide scheduling and reconfiguration for the HIRM aircraft:

(1) When a failure occurs the FDI system pinpoints the nature of it. As a result updated parameters are transmitted to the high fidelity model. Specifically, aerodynamic coefficients are modified and we assume that these modifications are performed by the FDI system. This is appropriate for structural failures. In the case of certain actuator failures such as jamming or reduced movement, information is passed to the $MBPC$ controller as modifications of input constraints.
(2) A linear time-invariant model is obtained at each step, as described in Section 2.2. This is used by the $MBPC$ controller as its internal

model (the same model is used over the prediction horizon).

(3) The constrained $MBPC$ controller computes appropriate inputs to the plant. Giving it enough degrees of freedom (a large enough set of control inputs) enables it to keep the plant close to the required trajectory, under the assumption that any failures are compatible with this.

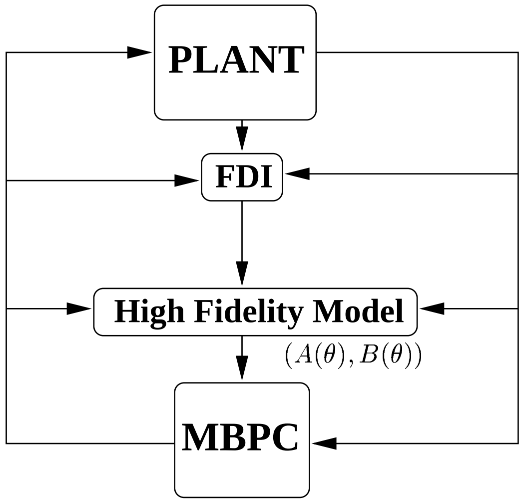

Fig. 1. The reconfiguration and scheduling $MBPC$ based strategy

We claim that the strategy provides the following two layers of fault tolerant control:

- Reconfiguration of control activities occurs if there are actuator failures which are consistent with maintenance of the required flight conditions.
- Implicit re-design of the control law occurs if there are structural failures, as a consequence of changes in the internal model.

3.3 *The controller design*

The controller design followed the general procedure which we have developed for conventional $MBPC$ control (Huzmezan and Maciejowski, 1996). This involved tuning the $MBPC$ controller for a plant model obtained by linearising the healthy high-fidelity model for an equilibrium point corresponding to a level flight with Mach number $M = 0.30$ at a hight of $H = 5000\ ft$ with parametric uncertainties in M of 3%. A sampling time of $T_s = 0.05\ s$ provided a good approximation over the whole open-loop bandwidth (the smallest constant which appears in the model is on the transfer function from symmetrical taileron (δ_{TS}) to pitch rate (q) and it is defined by a cross-over of about 10 ras/s).

In order to speed up the process the tuning was performed first for the unconstrained case. The control horizon was chosen to be the same as the number of states $N_u = 11$ but the small sampling time has determined a long prediction horizon of $N_2 = 60$ in order to predict 3 s ahead. This was enough to ensure the achievement of the performance criteria. The $MBPC$ control weighting matrix had to be made relatively big $R = \begin{bmatrix} 9\times10^4 & 3\times10^4 & 1\times10^4 \end{bmatrix}$, a typical choice for longitudinal channel of the aircraft. The $MBPC$ tracking weighting matrix $Q = \begin{bmatrix} 700 & 1 \end{bmatrix}$ reflects the requirements on the time response characteristics (rise time, settling time and overshoot) for the closed loop system. These were obtained after some trial and error, starting with unit values for both weighting matrices.

The next step in design, after checking the unconstrained closed loop behaviour, was to enforce the constraints and check the constrained $MBPC$ performance.

4. SIMULATION RESULTS FOR SEVERAL FAILURE SCENARIOS

4.1 *Actuator failures*

One of the most frequent failures encountered in real life is actuator failure. The reduction of control authority leads to reduced performance, or even instability.

The simulation result shown in Figure 2 shows at the system (HIRM) response when the canard actuator failed during a pitch rate demand of 6 deg/s. The step in pitch rate demand occurred at time 5 s followed by the failure, a stuck symmetrical canard, which occurred at time 8 s.

This failure, was represented by tightening the constraints on the allowed canard deflection in the $MBPC$ optimisation. Due to the $MBPC$ feature of handling constraints explicitly no other change was necessary in the structure of the controller.

The broken line in Figure 2 shows the response when no information about the failure is passed to the controller.

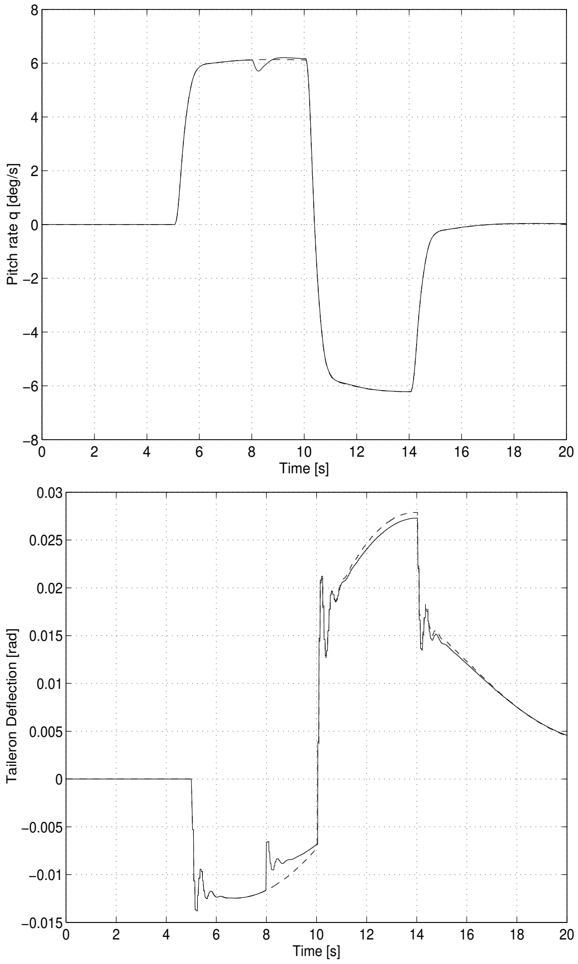

Fig. 2. The reconfiguration capabilities provided by the new approach in the case of actuators failures (nominal – broken, stuck canard – solid)

By looking at the performance criteria stated in the GARTEUR Design Challenge (Magni *et al.*, 1997), for this manoeuvre, we consider the controller performance in the presence of the failure to be satisfactory.

4.2 *Structural failures*

Dealing with a fighter aircraft, we can assume that one of the typical failures that its controller has to cope with are battle damages which in general are falling in the class of structural failures.

The simplest way to simulate structural failures in the aircraft high fidelity model is by means of the non-dimensional aerodynamic coefficients, which are modified accordingly. For instance a missing part of an aerodynamic surface translates into more drag and a reduced lift, which in their turn are translated into new values of the aerodynamic coefficients. This is according with a study (Hoak, 1978) which relates various types of structural failures to the aerodynamic model.

In our scenario we assume that such a structural failure, which changed the values of the aerodynamic coefficients by 20 %, occurred at time 8 s while a change of 25 m/s in speed set-point was demanded at time 5 s, see Figure 3. A fairly large set-point change was chosen as part of the scenario because we want to show the controller fault tolerant features.

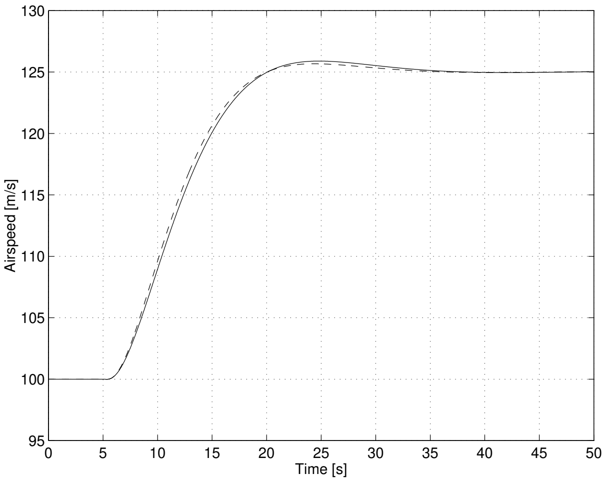

Fig. 3. The reconfiguration capabilities provided by the new approach in the case of structural failures (nominal – broken, 20 % change in aerodynamic coefficients – solid)

The performance of the reconfigurable flight controller, shown in Figure 3, complies with the criteria mentioned in GARTEUR Design Challenge document (Magni *et al.*, 1997).

4.3 *Combined failures*

Now we consider a simultaneous actuator and structural failure. This is typical of battle damage or of fatigue fracture.

In Figure 4 the performance of the controller is investigated when at time 5 s a change of 25 m/s in the air speed was demanded, followed at time 8 s by an actuator failure and at time 15 s by a structural failure similar with the ones described in Sections 4.1 and 4.2.

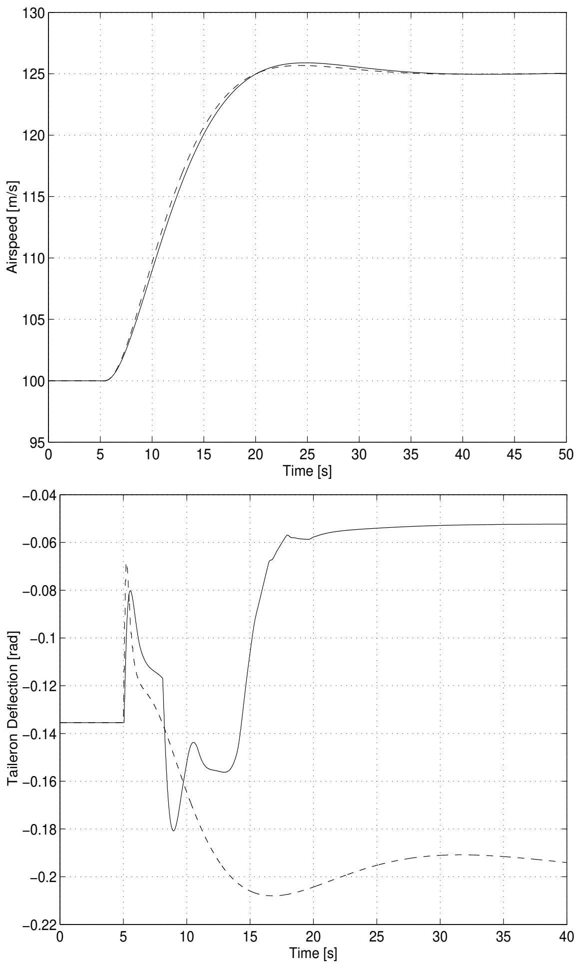

Fig. 4. The reconfiguration capabilities provided by the new approach in the case of a combined failure (nominal – broken, combined structural and actuator failure – solid)

5. CONCLUSIONS

The contribution of this paper is both at the conceptual and practical level. We have developed a strategy which provided scheduling and reconfiguration to the overall controller when a plant high-fidelity model is available.

The model chosen to illustrate the algorithm was subjected to several failure scenarios which shown the ability of the controller to meet robust performance criteria mentioned in the GARTEUR and DERA design challenges.

In terms of certification and the real time implementation there are a few more steps to be accomplished but according with the simulation results we can already consider this strategy as a potential future candidate for control reconfiguration providing the fact that an adequate hardware is available.

Further work will be concerned with wind tunnel tests performed with the physical model of the HIRM developed in our research establishment

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