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FAULT TOLERANT CONTROL IN DYNAMIC SYSTEMS

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Abstract: In this paper a method for fault tolerant control in dynamic systems is presented. In an integrated design, the proposed approach is composed of two stages. The first step is the detection and isolation of the failed component while the second step is represented by the reconfiguration mechanism. It consists in the estimation of new control parameters after evaluation of the performance degradation. In this paper, we mainly focus on the reconfiguration mechanism. A simulation is given to illustrate the proposed approach.

Keywords: Fault Tolerance, Control reconfiguration, Fault Diagnosis, Gain scheduling

1. INTRODUCTION

Over the past two decades, the growing demand for reliability in industrial processes has drawn increasing attention to the problem of fault detection and isolation (FDI), but only a few studies have been dedicated to the related fault-tolerant control (FTC) problem. The objective of a Fault Tolerant Control system is to maintain current performances closed to desirable performances and preserve stability conditions in the presence of component and/or instrument faults ; in addition reduced performance could be accepted as a trade-off. FTC can be motivated by different goals depending on the application under consideration, for instance, safety in flight control or reliability or quality improvements in industrial processes.

Although FTC is a recent research topic in control theory, the idea of controlling a system that deviates from its nominal operating conditions has been investigated by many researchers. The methods for dealing with this problem usually stem from linear-quadratic, adaptive, or robust control. The problems to consider in the design of a fault-tolerant controller are quite particular: at first, the number of possible faults and consequently of actions is very large. Second, the occurrence of a fault can make the system evolve far from its normal operating conditions and sometimes leads to a drastic change in system behaviour. It is often a rapid change, and the time for accommodation is very short. Furthermore, correct isolation of the faulty component is required to react successfully, a rather difficult problem in the case of closed-loop systems. Finally, FTC is a multivariable problem with strong coupling between the different variables.

Various approaches for fault-tolerant control have been suggested in the literature (R.J. Patton, 1997). From the application view point, flight control systems have represented the main area of research, and only a few studies have been devoted to industrial processes. One of the main goals of this article is to show that these approaches are appropriate to such systems.

The paper is organized as follows. In section II a general formulation of the problem is given. The proposed approach in this paper is based on the use of fault and identification scheme combined with a control reconfiguration algorithm. In section III model based fault diagnosis is addressed. .A procedure for Fault accommodation based on convex optimisation is then introduced in section IV. It consists in determining a new set of control parameters so that the reconfigured performances are "closed", in some sense to the nominal ones. Finally, a simulation example is given in section V to illustrate the proposed method.

2. PROBLEM FORMULATION

Fault-tolerant control systems are characterized in this article by their capabilities, after fault occurrence, to recover performance close to the nominal desired performance. In addition, their ability to react successfully (stable) during a transient period between the fault occurrence and the performance recovery is an important feature Accommodation capability of a control system depends on many factors such as the severity of the fault, the robustness of the nominal system, and the actuators' redundancy.

Actually, fault-tolerant control concepts can be shared into "passive" and "active" approaches. The passive approach makes use of robust control techniques for ensuring that a closed-loop system remains insensitive to certain faults. When redundant actuators are available, methods dealing with this approach are also called reliable control methods

(R.J. Veillette *et al.*, 1992), (Q. Zhao and J. Jiang, 1998). In the active approach, a new set of control parameters is determined such that the faulty system reaches the nominal system performance. The principle of active approaches, illustrated by Fig. 1, is very simple. After the fault occurrence, the system deviates from its nominal operating point defined by its input/output variables to a faulty one . The goal of fault-tolerant control is to determine a new control law that takes the degraded system parameters into account and drives the system to a new operating point such that the main performances (stability, accuracy,...) are preserved (i.e., are as close as possible to the initial performances). It is therefore important to define precisely the degraded modes that are acceptable with regard to the required performances, since after the occurrence of faults, conventional feedback control design may result in unsatisfactory performance such as tracking error, instability, and so on.

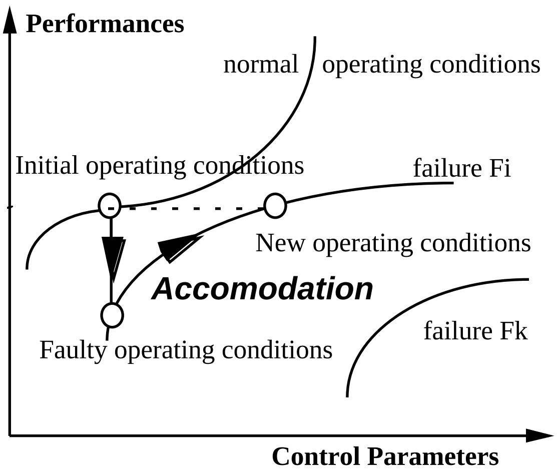

Figure 1: Principle for active FTC

When the exact model of the failed system is known, the control system can be accommodated so that system performances are recovered and the new system behaves as initially specified. Gao and Antsaklis, 1991, 1992 and Morse and Ossman, 1990 suggest a basic approach based on what they called the pseudo-inverse method. In practice, however, the faults are unanticipated and the model of the impaired system is not available. To overcome the limitations of conventional feedback control, new controllers have been developed with accommodation capabilities or tolerance to faults. These fault-tolerant controllers belong to different categories:

- Adaptive control seems to be the most natural approach to accommodate faults: the faults' effects appear as parameter changes and are identified on line, and the control law is reconfigured automatically based on new parameters (M. Bodson and J. Groszkiewicz, 1997), (Y. Ochi and K. Kanai, 1991), (H.E. Rausch, 1995), (F.A. Zaid *et al.*, 1991).
- Integrated approaches represent another trend (C.N. Nett *et al.*, 1998). They consist of the integration of fault monitoring and control procedures. In this case, the possible actuator or sensor faults are represented by signals and are estimated by the same algorithm that computes the control law (G.A. Murad *et al.*, 1996), (M.L. Tyler, 1994).
- The fault-tolerant control problem can also be formulated as a multiobjective problem based on the assumption that, like the uncertainties, the faults' effects can be expressed by means of linear fractional transformation (LFT). Following this methodology, a linear matrix inequality formulation for fault-tolerant controller synthesis has been recently introduced by Chen *et al.*, 1998.
- Finally, another way to achieve fault-tolerant control relies on supervised control where an FDI unit provides information about the location and time occurrence of any fault. Faults are compensated via an appropriate control law triggered according to diagnosis of the system. This can be achieved using gain scheduling (J. Jiang and Q. Zhao, 1998) or compensation via additive input design (H. Noura *et al.*, 1997), (D. Theilliol *et al.*, 1998). Methods combining model-based and knowledge or heuristic techniques were also successfully used to tune the controller (C. Aubrun *et al.*, 1993), (P. Ballé *et al.*, 1998), (Y. Ochi and K. Kanai, 1991), (R.J. Patton, 1997).

In this paper, the proposed fault tolerant controller is composed of 3 modules. The general concept of this approach is illustrated by Fig. 2 The FDI module consists of residual generation and residual evaluation. Second stage is performance evaluation and the third stage is represented by the reconfiguration mechanism. Fault detection and isolation must be achieved as soon as possible to avoid huge losses in system performance or catastrophic consequences.

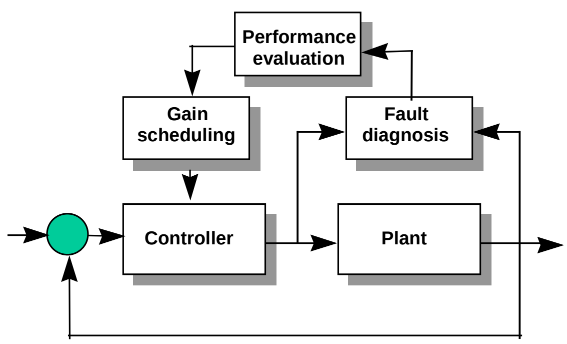

Figure 2: Architecture of a Fault tolerant controller

3. FAULT DIAGNOSIS & ESTIMATION

Diagnosis is the primary objective of fault tolerant control systems. This implies to design residuals which are very close to zero in fault free situations while clearly deviating from zero in the presence of faults and possess the ability to discriminate between all the possible modes of fault, which explains the use of the term isolation. The system under consideration is described by the following model:

$$\begin{aligned} x(t+1) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \qquad (1)$$

where $x(t) \in \Re^n$ is the state vector, $y(t) \in \Re^m$ the output observation vector, $u(t) \in \Re^p$ the input vector and *A*, *B* and *C* are known matrices of appropriate dimensions. Different additive and/or multiplicative faults may affect the system due to abnormal operation or to material aging. After the occurrence of a fault we assume that the model of the system becomes:

$$\begin{aligned} x(t+1) &= A_f x(t) + B_f u(t) \\ y(t) &= C_f x(t) + D_f u(t) \end{aligned} \qquad (2)$$

and the different matrices involved in the system description are modified according to

$$\begin{aligned} A_f &= A + \Delta F \\ B_f &= B + \Delta B \\ C_f &= C + \Delta C \\ D_f &= D + \Delta D \end{aligned} \qquad (3)$$

For instance a reduction of control effectiveness on the i-th actuator should be represented by:

$$B + \Delta B = \begin{bmatrix} B_1 & \cdots & (1+\alpha_i)B_i & \cdots & B_m \end{bmatrix} \quad (4)$$

and a in the case of a complete lose of the i-th actuator we would have: $\alpha_i = -1$.

Equations (2) of the degraded system can also be rewritten under the form:

$$\begin{aligned} x(t+1) &= Ax(t) + Bu(t) + Ef(t) \\ y(t) &= Cx(t) + Du(t) + Ff(t) \end{aligned} \qquad (5)$$

where *f(t)* represents an unknown input.

Starting with the model given in Eq. (1), the idea is to determine a residual vector generator of the form:

$$r(t)=S(q)\,y(t)+Q(q)\,u(t) \qquad (6)$$

where *Q(q)* and *S(q)* are transfer matrices determined so as to allow the residual vector *r(t)* to handle both detection and isolation. Our aim is to design a residual generator, so that the map from f to r fulfills specific requirements: a non-zero i-th component of f must induce a non-zero i-th component of r, and it cannot influence the other component of r. Thus, for a particular fault f_j the goal is to obtain a directional residual which should be governed by the following relation

$$r(t) = \Sigma(q) f(t) \qquad (7)$$

where $\Sigma(q)$ is a transfer matrices such as isolation . requirements are fulfilled as it is shown in (D. Theilliol *et al.*, 1998). For detection and isolation of a we suggest to use the following evaluation function:

$$\Psi(t) = \sum_{t=t_0}^{t} r_i^2(\tau) \qquad (8)$$

which gives the energy supported by the residual vector $\underline{r}(\omega / f_j) = \left[r_1(\omega / f_j), \ldots, r_p(\omega / f_j) \right]^T$ corresponding to the effect of the f_i fault mode. The appropriate fault detection and isolation test derives from the following relations:

$$\begin{cases} \Psi(\underline{r} / f_j) \geq Th(f_j) & \text{for } f_j \neq 0 \\ \Psi(\underline{r} / f_j) < Th(f_j) & \text{for } f_j = 0 \end{cases} \qquad (9)$$

where threshold $Th(f_j)$ depends upon the maximum amplitude of the fault.

4. CONTROL RECONFIGURATION

The principle of the method that we propose is to make the nominal system and the reconfigured system as closed as possible.

Let us consider the linear system described by the state space equations (1). In the fault free case (i.e. . f=0), with the objective function:

$$J = \frac{1}{2} \sum_{t=0}^{\infty} \left(x^T(t) Q x(t) + u^T(t) R u(t) \right) \qquad (10)$$

the controller which achieve the optimal cost is given by:

$$u_{opt}(t) = -K_{opt}(Q,R)\, x(t) \qquad (11)$$

where:

$$K_{opt} = R^{-1} B^T X \qquad (12)$$

and X=X(Q,R) is the unique positive definite solution of the algebraic Riccati equation:

$$A^T X + XA - XBR^{-1}B^T X + Q = 0 \qquad (13)$$

The occurrence of a fault leads to the modification of the system parameters. As stated in section II, we assume that an actuator fault modifies the parameters of the B matrix and that a component fault influences the parameters of the A matrix. The failed system is then given by:

$$\begin{aligned} x(t+1) &= A_f x(t) + B_f u(t) \\ y(t) &= C\, x(t) \end{aligned} \qquad (14)$$

Once the fault is detected, the goal of accommodation is to determine a new control law:

$$u_{recf}(t) = -K_{recf}(Q,R)x(t) \quad (15)$$

such that the performances of the failed system are close to the nominal ones. It is therefore required to restore the total control effort and consequently the system performances. This approach seems possible as long as the system dynamics, namely the A matrix, does not change with fault.

Let us consider the regulation performances:

$$\Phi_i = \int_{t_0}^{\infty} x_i^2 dt \quad 1 \le i \le m \quad (16)$$

and the control efforts:

$$\Phi_j = \int_{t_0}^{\infty} u_j^2 dt \quad 1 \le j \le p \quad (17)$$

Reconfiguration is a multi-criterion optimization problem where the following objective function:

$$\begin{aligned} &\Phi^0 = \lambda_1 \Phi_1^0 + \ldots. \lambda_L \Phi_L^0 \\ &\lambda_k \ge 0 \quad , k = 1,\ldots, L = m+p \end{aligned} \quad (18)$$

should be optimal in the normal operating conditions .
After the occurrence of a fault, the objective function becomes:

$$\begin{aligned} &\Phi^f = \lambda_1 \Phi_1^f + \ldots. \lambda_L \Phi_L^f \\ &\lambda_k \ge 0 \quad , k = 1,\ldots, L = m+p \end{aligned} \quad (19)$$

The goal is to design a new controller such as the actual performances are as closed as possible to the optimum in the failed conditions which give

$$(Q,R) = Arg \underset{Q,R}{Min} \left(\Phi^f (K_{recf}) - \Phi^0 (K_{opt}) \right) \quad (20)$$

Q and R are design parameters which make possible to balance fault accommodation performances and required energy.

The solution to this problem is given, using convex optimization techniques. The concept is illustrated by the Figure 3.

The optimization problem can be easily solved using a linear programming expressed as:

$$\begin{cases} \Phi(K_k) = \underset{K}{Min}\left(\Phi\right) \\ \Phi(K_i) + \dfrac{\partial \Phi^T}{\partial K_i}(K - K_i) \le \Phi(K), 1 \le i \le k \end{cases} \quad (21)$$

where $\Phi(K_i)$ and $\dfrac{\partial \Phi}{\partial K_i}$ are computed according to:

$$\begin{aligned} &\Phi_i = x(t_0)^T M_i x(t_0), i = 1,\ldots,m \\ &M_i A_f + A_f^T M_i + C_i^T C_i \\ &\qquad = M_i B_f R^{-1} B^T X + XBR^{-1} B_f M_i \end{aligned} \quad (22)$$

and:

$$\begin{aligned} &\Phi_j = x(t_0)^T P_j x(t_0), i = 1,\ldots,p \\ &P_j A_f + A_f^T P_j + D_j^T D_j \\ &\qquad = P_j B_f R^{-1} B^T X + XBR^{-1} B_f P_j \end{aligned} \quad (23)$$

Since the objective function is convex, it is shown that this algorithm converges to the optimum $K = K_{recf}$.

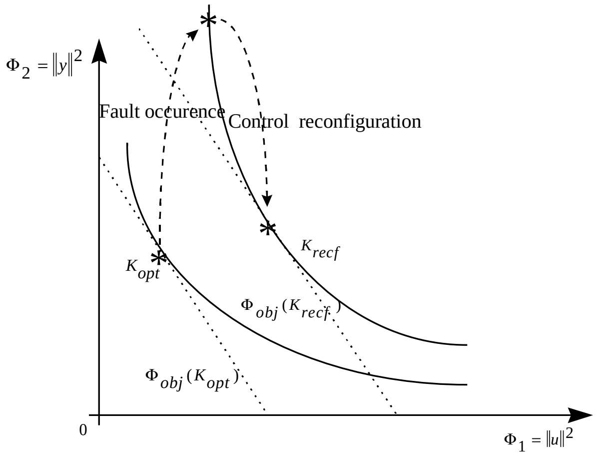

Figure 3: Control reconfiguration via gain scheduling

5. APPLICATION

For illustration and validation purposes, the proposed method was applied to a simulation example using an aircraft model considered by Wu *et al.*, 2000. The example considers longitudinal dynamics only, which is taken to be decoupled from lateral directional dynamics.

Model of the sytem satisfy to Eq (1) with the following parameters matrices:

$$A = \begin{bmatrix} -.0226 & -36.6 & -18.9 & -32.1 \\ 0 & -1.9 & 0.983 & 0 \\ 0.0123 & -11.7 & -2.63 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$
$$B = \begin{bmatrix} 0 & 0 \\ -0.414 & 0 \\ -77.8 & 22.4 \\ 0 & 0 \end{bmatrix} \quad (24)$$

The state variables are respectively forward velocity, angle of attack, pitch rate and pitch angle.Control inputs are elevon and carnard. It is supposed for simplification that all the state variables are measured.

Under fault free conditions, an LQ controller is designed with following weighting matrices:

$$Q = diag(.0001,.0001,.0001,.0001)$$
$$R = diag(.01,.01)$$

On the results shown in the next figures a fault corresponding to a reduction of control effectiveness due to control surface impairment, (1^{st} input) has been simulated. Performance index given on 3D plot of figure 4 is computed with weighting factors set to 1. It shows that performance depends on the control effectiveness factor. It is clear also that a loss of performances can be compensated by changing the control parameters. We can see that by increasing the R(2,2) coefficient in the LQ controller design, it is possible to make the objective function recover performances close to the initial one. Figure 5 give plots illustrating the reconfiguration mechanism. Normal operating conditions, faulty operating conditions and reconfigured conditions as well are given. It is to be noticed that under faulty conditions, system is unstable. Reconfiguration is active at t=4. Note that an estimation of the effectiveness is not required. Actually, only the knowledge of the fault direction is required to select the control parameter to be adjusted according to the magnitude of the performance degradation.

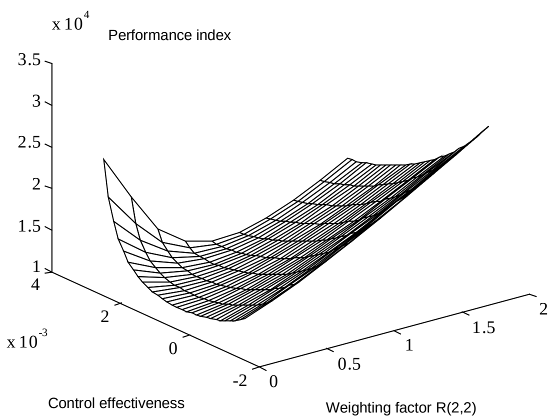

Figure 4: Objective function versus fault and control parameters

6. CONCLUSION

In this paper, the importance of fault accommodation in certain systems in order to preserve the safety of the system is emphasized. An indirect accommodation method based on fault detection and control reconfiguration is proposed. This method has been applied to an aircraft simulation and gave good results. Some aspects which are currently under study are the application of the algorithm to real process and the fundamental problem of robustness to parameter uncertainties and disturbances.

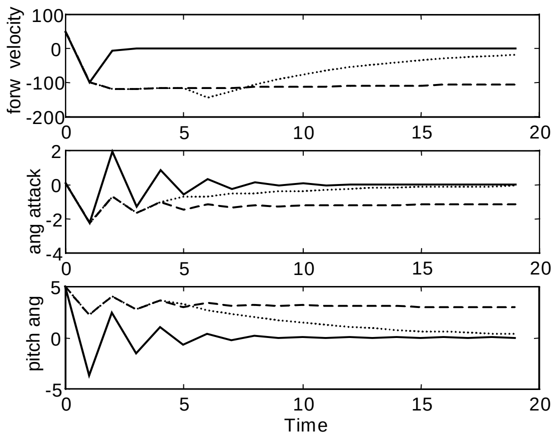

Figure 5: Time history of state variable: normal (—), faulty(--) operating conditions and reconfigured(…) operating conditions

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