Decentralized Adaptive Fault-Tolerant Control for Complex Systems with Actuator Faults

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In this paper, an adaptive fault-tolerant control scheme is extended to large-scale interconnected systems with actuator failures and external disturbances. Based on Lyapunov stability theory, a state feedback decentralized controller is designed to compensate for the fault and the disturbance effects, using the overlapping decomposition method. Applying the inclusion principle, the interconnected system is expanded in order to become disjoint subsystems. An adaptive controller is then synthesized separately for each obtained subsystem. The decentralized controller, designed for the expanded system, is finally contracted back to be implemented in the original space. An example of application illustrates the theoretical results and provides a comparative study with other robust and fault-tolerant methods.

1. Introduction

Many industrial complex processes, like power systems, water transportation networks, and large space structures, are physically distributed over a wide area and include subsystems that share a certain number of states [1–3]. Two control strategies are considered for such systems: centralized and decentralized feedback schemes [4]. The decentralized method has advantages in computation and implementation of control law and ensures stabilization of large-scale systems based on local state feedback, using the inclusion principle [5]. The original system will be expanded into a larger space in order to make overlapping subsystems disjoint, then decentralized controllers will be designed. Finally, the local controllers and the expanded system will be contracted to the original space for control law implementation [6]. Those systems, like other control systems, are susceptible to faults, which can attack actuators, sensors, the process itself, or the controller. Such defects may be worsened by closed-loop control systems, and faults can develop into malfunction of the loop. The closed-loop control action may hide a fault from being observed, which will easily cause production to stop or system malfunction at a plant level [7–10]. In that event, the fault diagnosis is insufficient and an adequate control scheme, called fault-tolerant control (FTC), is needed to ensure system stability even in a faulty case. FTC contributes to increased human and system safety and reliability. The main purpose of FTC is to ensure the specified performance of a system in a faulty case and to overcome the limitation of conventional feedback control [11, 12]. Most of the fault-tolerant design approaches can be broadly classified into two main categories, namely passive approaches [13–17] and active approaches [18–20]. In active FTC, the idea is to introduce a fault detection and isolation block in the control system. If a fault occurs, a supervisory system takes action and modifies the structure and/or the parameters of the feedback control system; consequently, a new set of control parameters is determined such that the faulty system reaches the nominal system performance. In contrast, in the passive FTC approach, a fixed compensator is designed to maintain (at least) stability if a fault occurs in the system. This approach, also called reliable control, uses robust control techniques to ensure that a closed-loop system remains insensitive to certain faults without the need for system reconfiguration and fault detection [12, 21]. Veillette [14] used a Riccati equation-based approach to develop a procedure for the design of a state-feedback controller, which could tolerate the outage within a selected subset of actuators while preserving the stability and the known quadratic performance bound. Yang et al. [15, 22] and Veillette et al. [13] proposed a controller that could guarantee locally asymptotic stability and H_∞ performance even when faults occur. However, the passive methods have a limited fault-tolerant capability. On the contrary, an FTC system based on active approaches can compensate for defects either by selecting a precomputed control law or by generating a new control strategy online. Another typical technique for fault compensation is based on the adaptive method [18, 23–25]. Ye et al. [20] considered an adaptive FTC scheme by actuator defects with application to flight control. Chandler et al. [26] and Smith et al. [27] have established system identification schemes appropriated to adaptive and reconfigurable control. The results are applied in flight control systems. Tao et al. [24, 28] have focused on adaptive FTC laws based on model reference tracking.

The purpose of this paper is to extend an adaptive FTC law used in [29] and [30] to the overlapped control of interconnected systems, using the inclusion principle.

2. Model Description and Decomposition

A linear time-invariant continuous-time interconnected system is considered, where the state vector $X(t)$ is partitioned into three blocks: $x_1(t)$, $x_2(t)$, and $x_3(t)$. The interconnection is restricted to two overlapping subsystems. The system S is governed by the following state-space representation:

$$\dot{X}(t) = A\, X(t) + B^1\, w(t) + B^2\, u(t), \tag{1}$$

where

$$X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{bmatrix}, u(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix},$$

$$B^1 = \begin{bmatrix} B_1^1 \\ B_2^1 \\ B_3^1 \end{bmatrix}, B^2 = \begin{bmatrix} B_{11}^2 & B_{12}^2 \\ B_{21}^2 & B_{22}^2 \\ B_{31}^2 & B_{32}^2 \end{bmatrix}, A = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix},$$

$$X(t) \in \mathbb{R}^n, x_1(t) \in \mathbb{R}^{n_1}, x_2(t) \in \mathbb{R}^{n_2},$$
$$x_3(t) \in \mathbb{R}^{n_3}, \text{ and } n = n_1 + n_2 + n_3.$$

The bounded external disturbances are denoted by $w(t) \in \mathbb{R}^q$, and $u(t) \in \mathbb{R}^m$ represents the control input. The matrices have appropriate dimensions.

To simplify the design process of the control law, the overlapping decomposition is used to extract the decoupled subsystems embedded with only the inter-area mode of interest. We consider the case with two overlapped subsystems in states [2, 31–35]. In this case, the state variables are decomposed into two groups:

$$z_1(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \text{and } z_2(t) = \begin{bmatrix} x_2(t) \\ x_3(t) \end{bmatrix},$$

with overlapping state variable $x_2(t)$, which is repeated in $Z(t)$. A new state vector $Z(t)$ is then defined as follows:

$$Z(t) = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \left[x_1^T,\ x_2^T,\ x_3^T,\ x_4^T\right]^T, \tag{2}$$

where $Z(t) \in \mathbb{R}^{\tilde{n}}$ and $\tilde{n} = n_1 + 2\,n_2 + n_3$.

The new state vector $Z(t)$ is obtained through the following linear transformation:

$$Z(t) = V\,X(t), \tag{3}$$

where

$$V = \begin{bmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & I_3 \end{bmatrix},\ V \in \mathbb{R}^{\tilde{n} \times n}.$$

I_1, I_2, and I_3 are identity matrices with dimensions related to $x_1(t)$, $x_2(t)$, and $x_3(t)$, respectively. The matrix V^+ denotes the pseudoinverse of the matrix V and verifies

$$V\,V^+ = I_{\tilde{n}}. \tag{4}$$

$I_{\tilde{n}}$ is an identity matrix with dimension $\tilde{n}$.

To decompose S into disjoint physical subsystems, it will be enlarged to a new system $\tilde{S}$. The expanded system $\tilde{S}$ includes the original system S according to the inclusion principle; this property ensures that the stability of $\tilde{S}$ implies the stability of S [2, 6, 35, 36]. The expanded system $\tilde{S}$ of S is defined by

$$\tilde{S} : \dot{Z}(t) = \tilde{A}\,Z(t) + \tilde{B}^1\,w(t) + \tilde{B}^2\,u(t), \tag{5}$$

where

$$\tilde{A} = V\,A\,V^+ + M = \begin{bmatrix} \tilde{A}_1 & \tilde{A}_{12} \\ \tilde{A}_{21} & \tilde{A}_2 \end{bmatrix},$$

$$\tilde{B}^1 = V\,B^1 = \begin{bmatrix} \tilde{B}_1^1 \\ \tilde{B}_2^1 \end{bmatrix},\ \tilde{B}^2 = V\,B^2 = \begin{bmatrix} \tilde{B}_1^2 & \tilde{B}_{12}^2 \\ \tilde{B}_{21}^2 & \tilde{B}_2^2 \end{bmatrix},$$

and $V^+\,M^i\,V = 0$ for all $i = 1, \ldots, \tilde{n}$. The complementary matrix M and the pseudoinverse matrix V^+ are referred to by:

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$$V^{+} = \left(V^{T}\, V\right)^{-1}\, V^{T} \text{ and } M = \begin{bmatrix} 0 & 0.5\, A_{12} & -0.5\, A_{12} & 0 \\ 0 & 0.5\, A_{22} & -0.5\, A_{22} & 0 \\ 0 & -0.5\, A_{22} & 0.5\, A_{22} & 0 \\ 0 & -0.5\, A_{32} & 0.5\, A_{32} & 0 \end{bmatrix}.$$

Complementary matrices are used in order to make the interconnection (off-diagonal) block matrices as sparse as possible, thus improving the decentralized control strategies for stabilization of the original system [31].

The expanded system $\tilde{S}$ can be decomposed into the following two interconnected overlapping subsystems:

$$\begin{aligned} \tilde{S}_1 : \dot{z}_1(t) = {} & \tilde{A}_1\, z_1(t) + \tilde{B}_1^2\, u_1(t) + \\ & \tilde{A}_{12}\, z_2(t) + \tilde{B}_{12}^2\, u_2(t) + \tilde{B}_1^1\, w(t), \end{aligned} \tag{6}$$

$$\begin{aligned} \tilde{S}_2 : \dot{z}_2(t) = {} & \tilde{A}_2\, z_2(t) + \tilde{B}_2^2\, u_2(t) + \\ & \tilde{A}_{21}\, z_1(t) + \tilde{B}_{21}^2\, u_1(t) + \tilde{B}_2^1\, w(t), \end{aligned} \tag{7}$$

where

$$\tilde{A}_1 = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \tilde{A}_{12} = \begin{bmatrix} 0 & A_{13} \\ 0 & A_{23} \end{bmatrix}, \tilde{A}_{21} = \begin{bmatrix} A_{21} & 0 \\ A_{31} & 0 \end{bmatrix},$$

$$\tilde{A}_2 = \begin{bmatrix} A_{22} & A_{23} \\ A_{32} & A_{33} \end{bmatrix}, \tilde{B}_1^2 = \begin{bmatrix} B_{11}^2 \\ B_{21}^2 \end{bmatrix}, \tilde{B}_{12}^2 = \begin{bmatrix} B_{12}^2 \\ B_{22}^2 \end{bmatrix},$$

$$\tilde{B}_{21}^2 = \begin{bmatrix} B_{21}^2 \\ B_{31}^2 \end{bmatrix}, \tilde{B}_2^2 = \begin{bmatrix} B_{22}^2 \\ B_{32}^2 \end{bmatrix}, \tilde{B}_1^1 = \begin{bmatrix} B_1^1 \\ B_2^1 \end{bmatrix}, \text{ and } \tilde{B}_2^1 = \begin{bmatrix} B_2^1 \\ B_3^1 \end{bmatrix}.$$

$\tilde{A}_{12}$, $\tilde{A}_{21}$, $\tilde{B}_{12}^2$, and $\tilde{B}_{21}^2$ characterize the interconnection matrices, which are made as sparse as possible to become a weak interconnection. $\tilde{A}_1$, $\tilde{A}_2$, $\tilde{B}_1^2$, and $\tilde{B}_2^2$ define the following two decoupled subsystems:

$$\tilde{S}_{d\,1} : \dot{z}_1(t) = \tilde{A}_1\, z_1(t) + \tilde{B}_1^2\, u_1(t) + \tilde{B}_1^1\, w(t) \tag{8}$$

and

$$\tilde{S}_{d\,2} : \dot{z}_2(t) = \tilde{A}_2\, z_2(t) + \tilde{B}_2^2\, u_2(t) + \tilde{B}_2^1\, w(t). \tag{9}$$

The described decomposition method is illustrated in Figure 1.

In order to generate the decentralized control laws, the interconnection between the two subsystems $\tilde{S}_1$ and $\tilde{S}_2$ is considered as a perturbation and then neglected. Consequently, the asymptotic stability of the system $\tilde{S}$ is ensured by the synthesis of local controllers for the subsystems $\tilde{S}_{d1}$ and $\tilde{S}_{d2}$ [33, 35]. If the expanded system $\tilde{S}$ can be stabilized with a decentralized controller $u = \tilde{k}\,Z$, then the original system S is stabilized using the contracted control law $u = k\,Z$, where $k = \tilde{k}\,V$, which represents an overlapping control law [2]; see Figure 2.

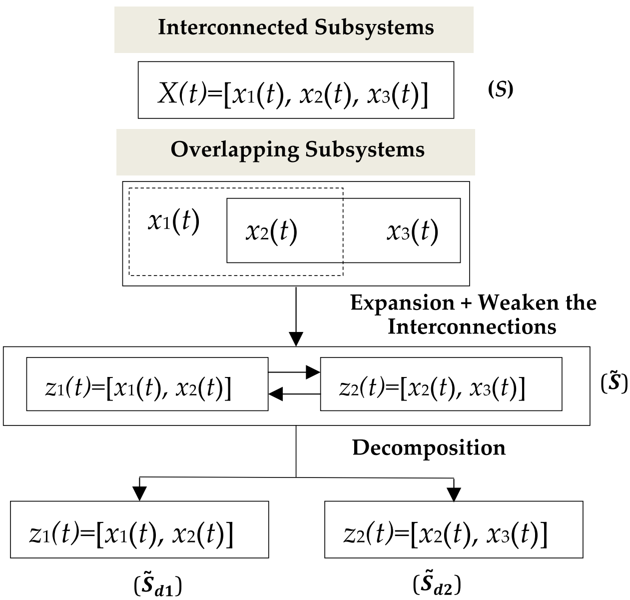

Figure 1. Overlapping decomposition of interconnected systems.

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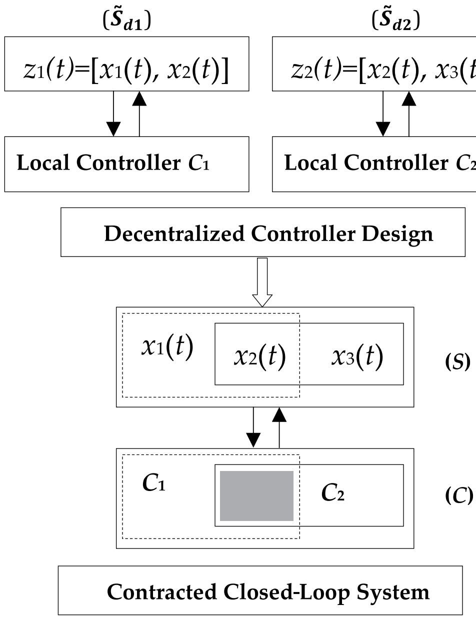

Figure 2. Overlapping controller design.

3. Adaptive Fault-Tolerant Control

Decentralized control of interconnected systems is based, in most cases, on local states feedback. The gain of such a control scheme depends on the strength of the interconnections. More often than not, the fixed-gain controllers become irrelevant following the unknown size of the interconnection between the subsystems. In such a situation, adaptive control will be used to adjust the gains to ensure stability of the original system [31, 37]. The goal is to design an adaptive fault-tolerant controller that could guarantee stability even in the presence of actuator faults and external disturbance.

3.1 Problem Formulation and Failure Model

For the i^{th} actuator $u_i(t)$, $i = 1, \ldots, m$, let $u_i^F(t)$ be the signal from the failed actuator. Consequently, the i^{th} actuator fault model can be represented as follows [9, 13, 14, 30, 38]:

$$u_i^F(t) = \rho_i(t)\, u_i(t), \tag{10}$$

where $\rho_i(t)$ is the actuator efficiency factor, which describes the loss of effectiveness in the i^{th} actuator. It can be bounded as follows:

$$0 \leq \underline{\rho}_i \leq \rho_i(t) \leq \overline{\rho}_i, \tag{11}$$

where $\underline{\rho}_i$ and $\overline{\rho}_i$ indicate, respectively, the known lower and upper bounds of $\rho_i(t)$. The following fault scenarios are distinguished: The situation $\underline{\rho}_i = \overline{\rho}_i = 1$ corresponds to the fault-free case; that is, $u_i^F(t) = u_i(t)$. $\underline{\rho}_i > 0$ covers the case of partial failure of the actuator $u_i(t)$. Finally, if $\underline{\rho}_i = \overline{\rho}_i = 0$, then we have $u_i(t) = 0$, which means outage of the i^{th} actuator.

If we denote by $\rho(t) = \text{diag}(\rho_1(t), \ldots, \rho_m(t))$ the global efficiency factor, we can get the failure model in the following compact form:

$$u^F(t) = \rho(t)\, u(t). \tag{12}$$

3.2 Control Law Design

The problem under consideration is to design an adaptive fault-tolerant controller such that the resulting closed loop is asymptotically stable not only when all system components are operational, but also in case of some actuator failures. The control law adopted in this paper has the following form [30, 39, 40]:

$$u\,(t) = \hat{K}_1(t)\, X(t) + K_2(t), \tag{13}$$

where $\hat{K}_1(t) = \left[\hat{K}_{1,1}(t), \ldots \hat{K}_{1,m}(t)\right]^T \in \mathfrak{R}^{m\,x\,n}$ and
$K_2(t) = \left[K_{2,1}(t), \ldots, K_{2,m}(t)\right]^T \in \mathfrak{R}^m$.

$\hat{K}_1(t)$ is updated using the following adaptive law:

$$\frac{d\,\hat{K}_{1,i}(t)}{d\,t} = -\Gamma_i\, X\, X^T\, P\, b_{2\,i}, \tag{14}$$

where Γ_i is any positive constant and $b_{2\,i}$, $i = 1, \ldots, m$, is the i^{th} column of B_2; $K_2(t)$ is expressed as follows:

$$K_2(t) = \frac{-\left(X^T\, P\, B_2\right)^T \beta \left\|X^T\, P\, B_2\right\| \hat{k}_3(t)}{\left\|X^T\, P\, B_2\right\|^2 \alpha}, \tag{15}$$

where α and β are suitable positive constants satisfying

$$\alpha \left\|X^T\, P\, B_2\, \right\|^2 \leq \beta \left\|B_2^T\, P\, X\, \sqrt{\rho}\, \right\|^2, \tag{16}$$

and $\hat{k}_3(t)$ is tuned by the following adaptive law:

$$\frac{d\,\hat{k}_3(t)}{d\,x} = \gamma \left\| X^T P B_2 \right\|, \tag{17}$$

where γ is any positive constant and P is a positive definite matrix. The asymptotic stability requires that the time derivative of a given positive Lyapunov functional V be negative. The following Lyapunov functional candidate will be used to prove the system stability [30, 39, 40]:

$$V\left(X, \tilde{K}_1, \tilde{k}_3\right) = X^T P X + \sum_{i=1}^{m} \tilde{K}_{1,i}^T \Gamma_i^{-1} \tilde{K}_{1,i} + \gamma^{-1} \tilde{k}_3^2, \tag{18}$$

where $\tilde{K}_{1,i}(t) = \hat{K}_{1,i}(t) - K_{1,i}$ and $\tilde{k}_3(t) = \hat{k}_3(t) - k_3$; and $K_{1,i}$ and k_3 are unknown constants. P is a symmetric and positive definite matrix satisfying, if (A, B_2) is stabilizable, the following Lyapunov equation:

$$\left(A + B_2\, \rho\, \hat{K}_1\right)^T P + P\left(A + B_2\, \rho\, \hat{K}_1\right) = -\,Q. \tag{19}$$

Q is any given positive definite symmetric matrix. It is clear that the Lyapunov functional candidate V is positive. Using equation (16), the time derivative of V for $t > 0$ can be transformed into the following inequality:

$$\begin{aligned} \dot{V}\left(X, \tilde{K}_1, \tilde{k}_3\right) \leq\ & X^T\Big[\left(A + B_2\, \rho\, \hat{K}_1\right)^T P + \\ & P\left(A + B_2\, \rho\, \hat{K}_1\right)\Big] X - 2\left\| X^T P B_2 \right\| \hat{k}_3 + \\ & 2\left\| X^T P B_2 \right\| \|F\|\, \overline{w} + \sum_{i=1}^{m} \tilde{K}_{1,i}^T \Gamma_i^{-1} \tilde{K}_{1,i} + \gamma^{-1} \tilde{k}_3^2. \end{aligned} \tag{20}$$

Knowing that $\overline{w}$ is an unknown bounded constant, there exists a constant k_3 verifying [30, 39, 40]

$$\left\| X^T P B_2 \right\| \|F\|\, \overline{w} \leq \left\| X^T P B_2 \right\| k_3. \tag{21}$$

In the light of equations (14), (17), (19), and (21), the time derivative of the Lyapunov function can be rewritten as

$$\dot{V}\left(X, \tilde{K}_1, \tilde{k}_3\right) \leq -\, X^T Q X \prec 0. \tag{22}$$

The requirement that $\dot{V} \prec 0$, to ensure asymptotic stability, leads to the adaptive laws in equations (14) and (17).

The goal is to apply equation (13) to the expanded system $\tilde{S}$ and through this stabilization to guarantee stabilization of S after contraction. The stabilization of $\tilde{S}$ is ensured using the two independent subsystems of equations (8) and (9) issued from the decomposition of $\tilde{S}$. For each subsystem, an adaptive fault-tolerant controller of the form in equation (13) will then be designed. The local controllers $u_1(t)$ and $u_2(t)$ corresponding, respectively, to equations (8) and (9) are given by

$$\begin{cases} u_1(t) = \tilde{\hat{K}}_1^1(t)\ z_1(t) + \tilde{K}_2^1(t) \\ u_2(t) = \tilde{\hat{K}}_1^2(t)\ z_2(t) + \tilde{K}_2^2(t). \end{cases} \tag{23}$$

The expanded system $\tilde{S}$ can be stabilized with the following decentralized control [2, 4, 41]:

$$U_D(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \tilde{\hat{K}}_1(t)\, Z(t) + \tilde{K}_2(t), \tag{24}$$

where

$$\tilde{\hat{K}}_1(t) = \begin{bmatrix} \tilde{\hat{K}}_1^1(t) & 0 \\ 0 & \tilde{\hat{K}}_1^2(t) \end{bmatrix} \text{and } \tilde{K}_2(t) = \begin{bmatrix} \tilde{K}_2^1(t) \\ \tilde{K}_2^2(t) \end{bmatrix}.$$

Taking into account equation (2), the expanded gain $\tilde{\hat{K}}_1(t)$ can be expressed as

$$\tilde{\hat{K}}_1(t) = \begin{bmatrix} \tilde{\hat{K}}_{11}^1(t) & \tilde{\hat{K}}_{12}^1(t) & 0 & 0 \\ 0 & 0 & \tilde{\hat{K}}_{13}^2(t) & \tilde{\hat{K}}_{14}^2(t) \end{bmatrix}. \tag{25}$$

If the expanded system $\tilde{S}$ can be stabilized with the decentralized control law of equation (24), then the contraction of the controller to the original space allows the stabilization of the original system S by

$$U_D(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \hat{K}_1(t)\, X(t) + K_2(t), \tag{26}$$

where

$$\hat{K}_1(t) = \tilde{\hat{K}}_1(t)\, V = \begin{bmatrix} \tilde{\hat{K}}_{11}^1(t) & \tilde{\hat{K}}_{12}^1(t) & 0 \\ 0 & \tilde{\hat{K}}_{13}^2(t) & \tilde{\hat{K}}_{14}^2(t) \end{bmatrix}$$

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$$\text{and } K_2(t) = \begin{bmatrix} \tilde{K}_2^1(t) \\ \tilde{K}_2^2(t) \end{bmatrix}.$$

The controller gains will be calculated separately for $\tilde{S}_{d1}$ and $\tilde{S}_{d2}$, using the adaptive law equations (14), (15), (17), (23), and then contracted to the form of equation (26) (see Figure 3), which makes the controller design easier for high-ordered systems without neglecting the strong interconnections between the subsystems.

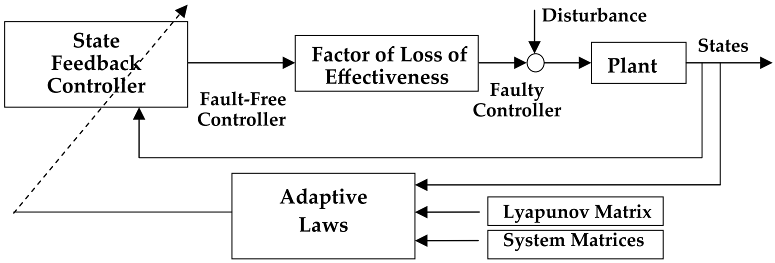

Figure 3. Block diagram of the control scheme.

4. Example of Application

To illustrate the effectiveness of the proposed method, we now give a numerical example. The state-space representation described by equation (1) is considered with the following system matrices:

$$A = \begin{bmatrix} -5 & 0.2 & 0 & 0.1 \\ -0.5 & -6 & -1 & 1 \\ -9 & -8 & -7 & 1 \\ 0.3 & 0.1 & -0.5 & -6 \end{bmatrix}, \; B_2 = \begin{bmatrix} 1 & 1.55 & 0.75 \\ 0.975 & 0.8 & 0.85 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$F = \begin{bmatrix} 1.5 & 1 \\ -2 & -1 \\ -1 & 0.5 \end{bmatrix}, \; w = \begin{bmatrix} -5 \sin(0.1\, t) \\ 5 \end{bmatrix}.$$

The considered actuator fault is a 40% loss of effectiveness in the first actuator, 60% in the second actuator, and 50% in the third actuator; that is, $\rho = \text{diag}(0.4, 0.6, 0.5)$.

The objective is to design an overlapping controller in order to compensate for actuator failure and to reject external disturbance. The expansion-contraction method will be used to achieve this purpose, using a transformation matrix V and a complementary matrix M given by

$$V = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, M = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.5 & 0.5 & 0 \\ 0 & 0 & -3.5 & 3.5 & 0 \\ 0 & 0 & 3.5 & -3.5 & 0 \\ 0 & 0 & 0.25 & -0.25 & 0 \end{bmatrix}.$$

The expanded system is defined using the following matrices:

$$\tilde{A} = \begin{bmatrix} -5 & 0.2 & 0 & 0 & 0.1 \\ -0.5 & -6 & -1 & 0 & 1 \\ -9 & -8 & -7 & 0 & 1 \\ -9 & -8 & 0 & -7 & 1 \\ 0.3 & 0.1 & 0 & -0.5 & -6 \end{bmatrix}$$

$$\text{and } \tilde{B} = \begin{bmatrix} 1 & 1.55 & 0.75 \\ 0.975 & 0.8 & 0.85 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

The state variables are decomposed into two groups: $z_1(t) = [x_1(t),\ x_2(t),\ x_3(t)]^T$ and $z_2(t) = [x_3(t),\ x_4(t)]^T$, with overlapping state variable $x_3(t)$. The new, expanded state vector $Z(t) = [x_1(t),\ x_2(t),\ x_3(t),\ x_3(t),\ x_4(t)]^T$ represents the expanded system, which will be divided into two weakly coupled subsystems. The gain matrix in the adaptive fault-tolerant decentralized controller of the expanded system has the following structure:

$$\tilde{\hat{K}}_1(t) = \begin{bmatrix} \tilde{\hat{K}}_{11}^1(t) & \tilde{\hat{K}}_{12}^1(t) & \tilde{\hat{K}}_{13}^1(t) & 0 & 0 \\ 0 & 0 & 0 & \tilde{\hat{K}}_{13}^2(t) & \tilde{\hat{K}}_{14}^2(t) \end{bmatrix}. \quad (27)$$

The contracted gain matrix of the original system corresponds to

$$\hat{K}_1(t) = \tilde{\hat{K}}_1(t)\, V = \begin{bmatrix} \tilde{\hat{K}}_{11}^1(t) & \tilde{\hat{K}}_{12}^1(t) & \tilde{\hat{K}}_{13}^1(t) & 0 \\ 0 & 0 & \tilde{\hat{K}}_{13}^2(t) & \tilde{\hat{K}}_{14}^2(t) \end{bmatrix}. \quad (28)$$

The system operates normally until the time instance $t = 3000$ s. From that moment, some faults occur in the actuators. Those actuators face an efficiency loss. The simulation results in the presence of actuator fault and external disturbance are given in Figures 4 and 5. Figure 4 depicts that the closed-loop FTC system becomes asymptotically stable in the presence of actuator faults and external disturbances. It is clear in Figure 5 that the controller gains $k_1(t)$ and $k_2(t)$ react instantly to fault occurrence.

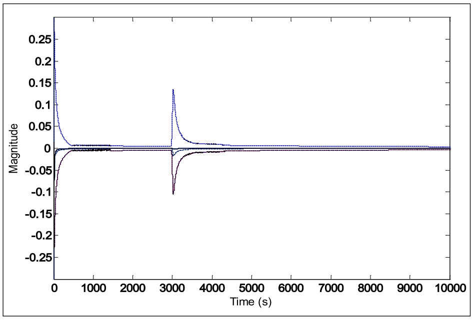

Figure 4. State trajectories in the faulty case.

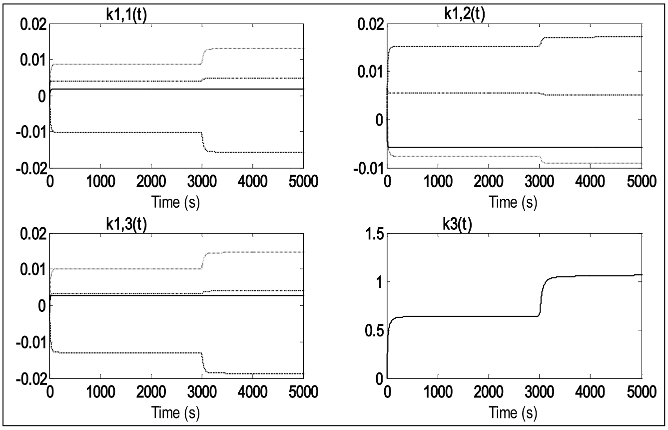

Figure 5. Controller gains $k_1(t)$ and $k_3(t)$ in the faulty case.

To compare the performance of the described method with other existing approaches, an optimal H_∞ (γ-iteration) controller will be considered first. Figures 6 and 7 show, respectively, the states before and after a fault occurs.

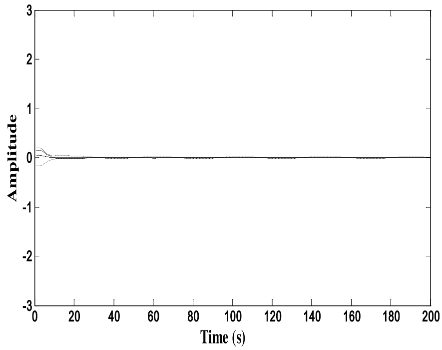

Figure 6. States by standard H_∞ controller without loss of effectiveness.

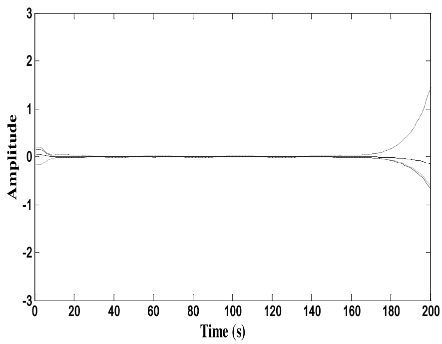

Figure 7. States by standard H_∞ controller after fault occurrence from time instant $t = 160$ s.

It can be seen from Figures 6 and 7 that the standard H_∞ controller stabilizes the closed-loop system in the fault-free case. When actuator efficiency decreases, the closed-loop system becomes unstable. The result is obvious because the standard H_∞ control method is robust against disturbances and not against faults.

Second, a reliable H_∞ control method will be compared with the designed adaptive controller. The approach considered reliable is a passive fault-tolerant technique providing guaranteed asymptotic stability and H_∞ performance in the presence of actuator faults; it was developed in [42] and extended to singularly perturbed systems in [10]. This control method will be applied in case of actuator loss of efficiency leading to the states time response illustrated in Figure 8.

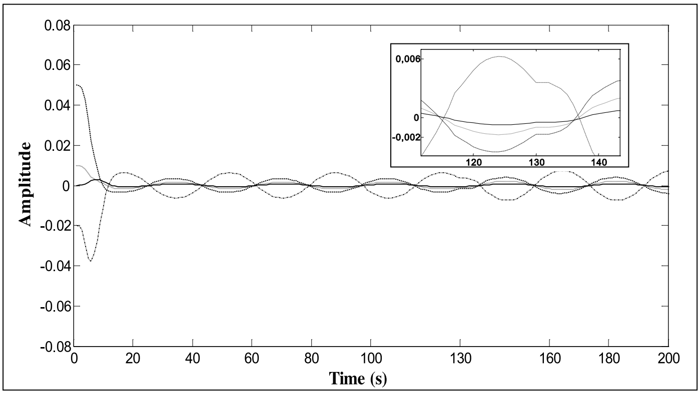

Figure 8. States by H_∞ reliable controller after fault occurrence from time instant $t = 130$ s with a zoom around $t = 130$ s.

It is clear in Figure 8 that the actuators' loss of effectiveness is compensated for using the fault-tolerant H_∞ control approach. The fault's effect on the states at the moment of its appearance is small (see the inset in Figure 8) compared with the designed adaptive control scheme. The constraints required for reliable H_∞ control, such as a priori knowledge of the extreme values of the factors of efficiency loss, make the adaptive FTC, which is considered as an active approach, more suitable.

5. Conclusion

A decentralized adaptive fault-tolerant control (FTC) has been proposed for stabilization of large-scale interconnected systems subject to actuator failures and external disturbances. The adopted actuator fault model covers the cases of normal operation, loss of effectiveness, and outage. State feedback controllers were designed for each overlapping subsystem obtained after decoupling of the expanded system. The expanded decentralized controller is then contracted to be implemented in the original system. The control gains are tuned using adaptation laws based on Lyapunov stability theory. An illustrative example covers a comparative study of the performances of the developed adaptive control method with other robust and reliable approaches. The adaptive approaches, considered as an active method, compensate for the fault effect without recourse to a diagnosis block, whereas robust methods use only techniques to overcome the perturbation effect. Even the extended forms of robust approaches, called passive approaches, present a fixed-parameter compensator, which ensures that the closed-loop system remains insensitive only to a priori known faults [10]. Compared with reliable control techniques, like H_∞ reliable control, the adaptive control law is reconfigurable through adaptive mechanisms and needs fewer constraints.

The main contribution of this paper is the extension of adaptive FTC to interconnected systems with actuator fault, using the inclusion principle. Additionally, the controller design is based on decoupled subsystems with lower order; this control strategy simplifies the controller synthesis of large-scale systems.

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