CENTRALIZED AND DECENTRALIZED ADAPTIVE FAULT-TOLERANT CONTROL APPLIED TO INTERCONNECTED AND NETWORKED CONTROL SYSTEM

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ABSTRACT

In this work, we focus on monitoring and reconfiguration of an Adaptive Model Reference (MRA) Fault-Tolerant Control (FTC) for large-scale system. This particular class presents an interconnected and networked control system (INCS). Moreover, the system can be decomposed into N-interconnected subsystems communicating with network. Then the global output of INCS and one or more outputs of N-interconnected and networked control subsystems are attacked by sensor faults. Therefore, an active Fault-Tolerant (FT) approach, say the model reference adaptive control of linear systems, is used in order to guarantee not only the stability of an overall INCS globally, but also all local stabilities of N-networked control subsystems with strong interactions, delay and additive faults. Moreover, two architectures: centralized and decentralized adaptive controllers are designed to compensate the sensor faults for different internal structures of systems which are subject of this paper. The law adaptations which make the different faulty systems stable are given. A simulation example of an overall INCS consisting of three interconnected and networked control subsystems and involving stabilization of unstable steady-states is used to demonstrate the efficiency of the proposed approach.

Keywords: adaptive control, centralized control, decentralized control, fault-tolerant control (FTC), interconnected system, networked control system (NCS), reference model (RM), sensor failure

1. INTRODUCTION

The notion of Fault-Tolerant adaptive control has been an active area of research (Blanke and al 2003, Bodson and al 1997, Patton 1997, Patton and al 1997). The theory of large-scale systems is devoted to the problems that arise from some difficulties (Ioannou and al 1985, Huang and al 2010, Lina and al 2006, Mahmoud 1997, Patton and al 2007):

-Dimensionality;
-Information structure constraints;
-Uncertainty;
-Delays.

A system is considered large-scale if it is necessary to partition the given analysis or synthesis into manageable sub-problems. As a result, the overall system is no longer controlled by a centralized controller but by several independent controllers which all together represent a decentralized controller. This is the fundamental difference between feedback control of small and large systems. On one hand, the development in this direction has reached a level of important applications where adaptive controllers are used to enhance stability and improve operating conditions of defective systems (Bodson and al 1997, Ioannou and al 1985, Mahmoud 1997, Tsai and al 2009). On the other hand, her theory is developed to make a general practical use of adaptive controllers in both large-scale and networked control systems [Ioannou and al 1985, Mahmoud 1997, Patton and al 2007). In interconnected and networked control systems, there will be more adaptive controllers located at different, possibly distant units, and in control centers. Besides, the dynamic of each local subsystem is not known exactly and the local outputs are corrupted with noise disturbances and faults via network control. In this paper, centralized and decentralized adaptive FTC based on reference model is included in presence of all interactions and over medium of communication between each subsystem. Two structures of adaptive controllers for interconnected and networked system is proposed (Bakule 2008, Challouf and al 2009, Hasheng 2003, Hovakimyan and al 2006, Sundarapandian 2005). Each adaptive controller is designed to compensate the additive faulty sensor. The stability of the overall adaptive control scheme is established.

The paper is organized as follows: Section 2 recalls the interconnected and networked control system modernization. Also, it represents the controller synthesis for LTI and continuous time systems. A simulation example of three interconnected and networked control subsystems subject to sensor faults is used in Section 3 to illustrate the effectiveness and performance of the two architecture (centralized and decentralized) active fault tolerant control system. Finally, a conclusion is included.

2. PROBLEM STATEMENT

2.1. Interconnected System

This class of the large-scale system can be composed of N-interconnected subsystems [Ioannou and al 1985, Mahmoud 1997].

Consider an overall interconnected system which is given by the following state spaces:

$$\left(S_p\right)\begin{cases} X_p\left(t\right)=A_pX_p\left(t\right)+B_pU_p\left(t\right)+D_pw_p(t) \\ Y_p\left(t\right)=C_pX_p\left(t\right)+D_pU_p\left(t\right)+V_pv_p(t) \\ X_p\left(0\right)=\varphi(t) \end{cases} \quad (1)$$

The index p designs the processus parameters.

A_p, B_p, C_p, D and V are the parameters system with appropriate dimensions.

On the other hand,

$X_p\left(t\right)\in\mathbb{R}^n, U_p\left(t\right)\in\mathbb{R}^m, Y_p\left(t\right)\in\mathbb{R}^q$

and $W_p\left(t\right)\in\mathbb{R}^p$ and $V_p\left(t\right)\in\mathbb{R}^p$ are the state vector, the control vector, the output vector and the external disturbance vectors respectively.

As black as this class of the large-scale system contains N-interconnected subsystems and based on equation (1), the partitioned matrix X_p, U_p and Y_p are:

$$X_p\left(t\right)=\left[X_{p1}^T,X_{p2}^T,...,X_{pN}^T\right]^T. \quad (2)$$

$$U_p\left(t\right)=\left[U_{p1}^T,U_{p2}^T,...,U_{pN}^T\right]^T. \quad (3)$$

$$Y_p\left(t\right)=\left[Y_{p1}^T,Y_{p2}^T,...,Y_{pN}^T\right]^T. \quad (4)$$

$$w_p\left(t\right)=\left[w_{p1}^T,w_{p2}^T,...,w_{pN}^T\right]^T. \quad (5)$$

In addition, the appropriates matrix A_p, B_p, C_p, D_p and V_p be partitioned as follows:

$$A_p=\begin{bmatrix} A_{p1} & A_{p12} & \cdots & A_{p1N} \\ \vdots & \vdots & & \vdots \\ A_{pN1} & A_{pN2} & \cdots & A_{pN} \end{bmatrix}. \quad (6)$$

$$B_p=\begin{bmatrix} B_{p1} & B_{p12} & \cdots & B_{p1N} \\ \vdots & \vdots & & \vdots \\ B_{pN1} & B_{pN2} & \cdots & B_{pN} \end{bmatrix}. \quad (7)$$

The matrix B will be full column rank.

$$C_p=\left[C_{p1} \quad C_{p2} \quad ,\cdots, \quad C_{pN}\right]. \quad (8)$$

and

$$v_p=\left[v_{p1} \quad v_{p2} \quad ,\cdots, \quad v_{pN}\right]. \quad (9)$$

Besides, the matrix \$A_p\$ can be viewed as an interconnected matrix, too, consisting N-subsystems defined by them appropriates matrices (A_{pi}, B_{pi}, C_{pi}), i=1,.., N.

So, we can write:

$$n=\sum_{i=1}^{N}n_i, m=\sum_{i=1}^{N}m_i, p=\sum_{i=1}^{N}p_i \text{ and } q=\sum_{i=1}^{N}q_i. \quad (10)$$

Consequently, the parameters of an overall system (S) depend essentially on the parameters of N-interconnected subsystems (S_i) which constituting (Ioannou and al 1985). In point of i[th] subsystem is instable, the global system is also instable.

Like that a global system (S) can regroups N-interconnected subsystems (S_i), the equation (1) can be rewritten into matrix form decomposing in all N-interconnected subsystems as follows:

$$(S_i):\begin{cases} \dot{X}_{pi}(s)=A_{pi}X_{pi}(s)+B_{pi}U_{pi}(s) \\ \qquad +\sum_{j\neq i}\left(G_{pij}g_{pij}(s)+D_{pij}W_{pij}(s)\right) \\ Y_{pi}(s)=C_{pi}X_{pi}(s)+L_{pi}V_{pi}(s) \quad ;i,j=1,...,N. \\ X_i(0)=\varphi_i(t) \end{cases} \quad (11)$$

Where: $X_{pi}\in\mathbb{R}^{n_i}, U_{pi}\in\mathbb{R}^{m_i} \text{ and } Y_{pi}\in\mathbb{R}^{q_i}$ are respectively the local states, the control and the output of the subsystems (S_i).

$A_{pi}\in\mathbb{R}^{n_i\times n_i}, B_{pi}\in\mathbb{R}^{n_i\times m_i} \text{ and } C_{pi}\in\mathbb{R}^{q_i\times n_i}$ are respectively the parametric matrix of the local states, the control and the output of the i[th] processus coupled with j[th] subsystems (S_j).

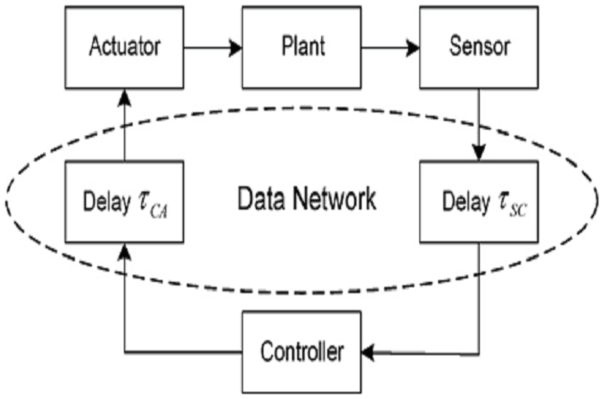

Figure1: Internal Structure of NCS

2.2. NCS model

The stage of modeling is rather significant at the time of the study of a process. The systems considered in this work belong to a particular class. They are the systems ordered by a medium of communication, they are known still by the systems ordered in network (NCS) [7,8,9]. This class of the system presents the phenomenon of delay in their dynamic of which its structure is illustrated by the fig.2:

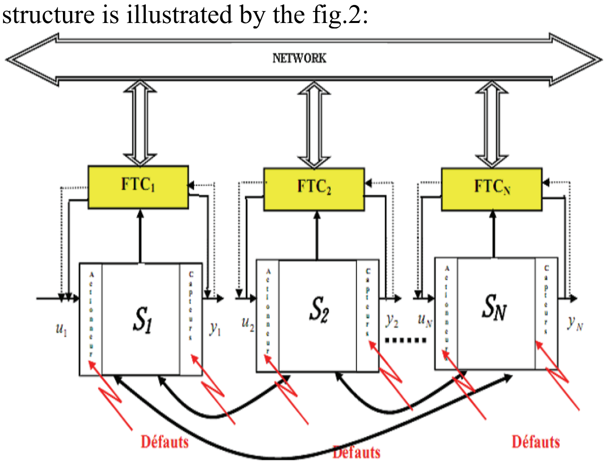

Figure 2: Structure of co-operative Interconnected NCSs and FTC

Contrary to the ordinary systems whose temporal evolutions can be given starting from the value of state X at the moment present $\dot{X}(t) = f\left(t, X_p(t)\right)$. Those of the systems ordered in network depend primarily on of the last values of the state $X_p(t)$. Moreover, the latter present the phenomena of delay and the losses or duplications of the messages during the transmission of the data control/actuator: τ_{cA} and sensor/control: τ_{sc}.

Generally, three working frameworks are used to represent a late system: models on ring, infinite models of dimension on operators and models in the form of differential equations. In this present work, concerning the stability on the one hand and the modeling of communication TCP on the other hand, we are interested in the effects of the delay in dynamics of the NCS. Plus precisely, we thus consider systems (eq.1) rewritten in the form:

$$\left(S_p\right)\begin{cases} X_p(t) = A_p X_p(t) + B_p U_p(t-\tau) + D_p w_p(t) \\ Y_p(t) = C_p X_p(t) + D_p U_p(t-\tau) + V_p v_p(t) \\ X_p(0) = \varphi(t) \end{cases} . \quad (12)$$

At the time of the phase of modeling, as well as the matrices defining a model, it is essential to determine the type of delay which affects the system (see fig 1).

There are three principal categories of delay:

(a) delay in known;

(b) raised delay;

(c) limited delay.

The delay can be between control/actuator and/or sensor/control that as (see fig.1):

$$\tau = \tau_{sc} + \tau_{cA} \quad (13)$$

Where:

$$0 \le \tau_{\min} \le \tau \le \tau_{\max} . \quad (14)$$

τ_{min} and τ_{max} represent respectively the minimum and maximum values of delay. All MIMO transfer matrix representations have appropriate dimensions and are proper real-rational matrices, stabilisable and detectable. A state space rational proper transfer - function is denoted by:

$$Sys_p = \frac{U_p}{Y_p} = \begin{bmatrix} A_p & B_p \\ C_p & D_p \end{bmatrix}$$
$$= C_p\left(sI - A_p\right)^{-1} B_p + D_p \quad (15)$$

2.3. Model Reference Adaptive FTC design

Consider a LTI system defined by eq.12. To accommodate the last system, we were implementing adaptive FTC. His principal is explained by fig.2 offering the structure of co-operative INCSs and FTC. The last method is based on reference model. It proves the aptitude to reach the characteristics specified by the reference model in presence of additive faults on system [11, 12, 13, 14, 15]. The last idea is illustrated by fig.3. Based on fig.3 and in the time domain, the overall reference model is described by the equation:

$$\dot{Y}_m(t) = A_m Y_m(t) + B_m r(t) \quad (16)$$

The index m designs the known reference model parameters.

In this part, we apply the direct method of the fault tolerant adaptive control. The control input is given by:

$$U_P(t) = (C_0(t) r(t)) + (G_0(t) Y_p(t)). \quad (17)$$

With C_0(t) and G_0(t) are the parameters of the adjustable controller.

The derivation of time response plant is given by:

$$\dot{Y}_p(t) = (C_p A_p + C_p B_p G_0) X_p(t) + C_p B_p C_0 r(t) \quad (18)$$

When $C_0(t) = C_0^*$ and $G_0(t) = C_0^*$

The motivation being that there exist nominal parameter values of the adaptive controller:

$$\begin{cases} C_0^* = (C_p B_p)^{-1} B_m \\ G_0^* = (C_p B_p)^{-1}(A_m C_p - C_p A_p) \end{cases} \tag{19}$$

The update laws are given by:

$$\dot{\phi} = \begin{bmatrix} \dot{\phi}_r(t) \\ \dot{\phi}_Y(t) \end{bmatrix} = \begin{bmatrix} \dot{C}_0(t) = -g\, e_0(t) r(t) \\ \dot{G}_0(t) = -g\, e_0(t) Y(t) \end{bmatrix} \tag{20}$$

Thus, the expression of the adaptive law control becomes:

$$U(t) = ((\phi_r(t) - C_0^*) r(t)) + ((\phi_Y(t) - G_0^*) Y_p(t)) \tag{21}$$

Since, the error dynamic equation between the plant time responses $Y_{pf}(t)$ and reference model $Y_m(t)$ with the adjustable parameters of the regulator is given by:

$$\dot{e}_0(t) = A_m e_0 + (C_p B_p) \begin{bmatrix} (C_0 - C_0^*) r(t) \\ +(G_0 - G_0^*) X_p(t) \end{bmatrix} \tag{22}$$

Now let us consider for the parameters error the following notations:

$$\begin{bmatrix} \phi_r(t) \\ \phi_Y(t) \end{bmatrix} = \begin{bmatrix} C_0(t) - C_0^* \\ G_0(t) - G_0^* \end{bmatrix} \tag{23}$$

In the following representation, the right-hand sides only contain states (e_0 ,ϕ_r ,ϕ_Y) Consider then the Lyapunov function candidate corresponding:

$$V(e_0, \phi_r, \phi_Y) = \frac{e_0^2}{2} + \frac{k_p}{2g}(\phi_r^2 + \phi_Y^2) \tag{24}$$

Taking the derivative of Lyapunov function:

$$\dot{V}(e_0, \phi_r, \phi_Y) = -A_m e_0^2 \tag{25}$$

where $A_m>0$ is arbitrarily chosen by the designer.

So that the system is stable, it is necessary that $V \geq 0$ and $\dot{V} \leq 0$ what is checked. This involves that the adaptive system is stable in the sense of Lyapunov (Bakule2008).

3. THREE INTERCONNECTED AND NETWORKED CONTROL SUBSYSTEMS EXAMPLE

In this simulation party, we interest at a numerical example where N=3 illustrated by figure 3 in order to demonstrate the efficiency of the proposed control.

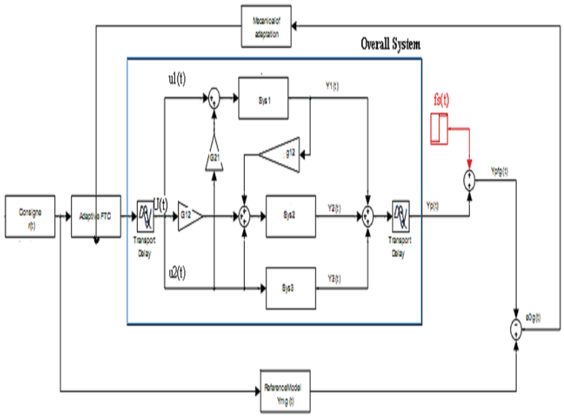

Figure 3: Functional diagram of Interconnected NCS in presence of sensor faulty

Consider the overall system (eq.1) consisting of three interconnected and networked control sub-systems (Sys_1), (Sys2) and (Sys_3) with unit reference input (r(t)=1). On one hand based on fig.2, the transfer function of overall interconnected networked control reference model (eq.17) is giving as follows:

$$Sys_m = \frac{Y_m}{U_m} = e^{-0.348s} \frac{3s^3 + 11.26s^2 + 13.14s + 4.703}{s^4 + 5.5s^3 + 11.06s^2 + 9.688s + 3.125}.$$

But, the transfer function of overall interconnected networked control system without external disturbances is giving as follows:

$$Sys_p = e^{-0.348s} \frac{3s^3 + 11.26s^2 + 13.14s + 4.703}{s^4 + 5.5s^3 + 11.06s^2 + 9.688s - 3.125}.$$

So reference to the last transfer function, the overall interconnected and networked control system Sys_p is unstable.

On the other hand, the interconnection vector functions are respectively: G_{12}=-0.5, G_{21}=0.5, g_{12}=-0.579 and the total delay is: τ= 0.348 where the delays into sensor/control and control/actuator are giving respectively: τ_{sc} = τ_{cA} = 0.174. The global Interconnected NCS (Sys_p) is unstable.

Then as the fault $f_s(t)$ is additive(fig.4) it can attack the total output $Y_p(t)$or one or more outputs $Y_p(t)$ of the total system Sys_p. It is clearly, at the moment t = 20sec, we generate the offset fault with amplitude 1.

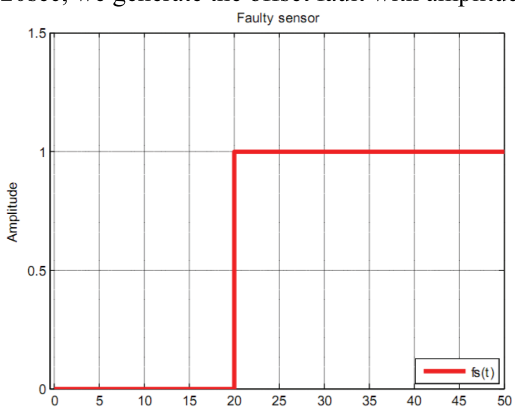

Figure 4: Offset fault

The time response $Y_{pf}(t)$ of the plant becomes:

$$Y_{pf}(t) = Y_p(t) + f_s(t), i = 1, \ldots, N. \tag{26}$$

We use the control law (18) for various types of faults. The figures (4) and (5) illustrate the trajectories of the overall INCS time responses Y_{pf}(t), the reference model Y_m(t) and the error e_0(t).

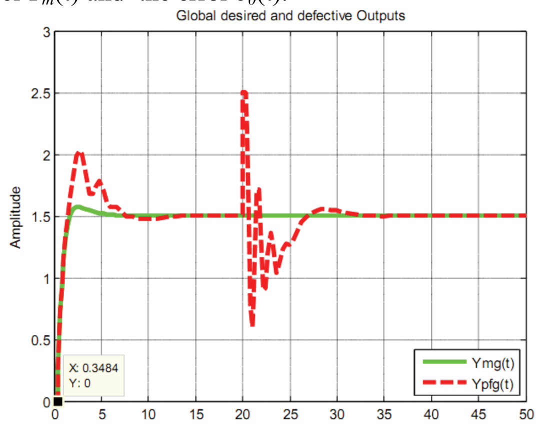

Figure 5: Dynamic global output responses via MR Adaptive FTC.

The figure 6 illustrates the dynamic global controls trajectories: U_p(t) were implemented on two different interconnected and networked control subsystems: Sys_{pi} i=1,2,3, into to accommodate the defective overall Interconnected NCS: Sys_{pf}.

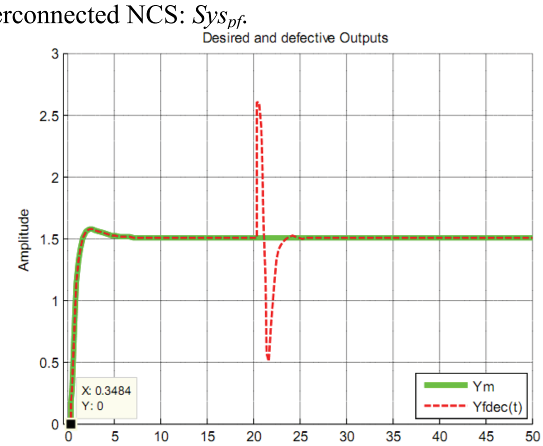

Figure 6: Dynamic distributed output responses via adaptive model reference FTC

4. MAIN RESULTS AND INTERPRETATIONS

Here, to study the influence and the differences between centralized and decentralized architecturally adaptive controllers based on reference model, the figure5 and figure 6 illustrate the various response trajectories. It is clearly that the accommodation of Interconnected NCS_f is realized by the proposed control laws such that are find simulation results. In addition, it is clearly that the adaptive FTC is implemented to three subsystems. They are LTI, continuous times, interconnected and networked control subsystems Sys_i,i=1,2,3. All constitute an overall interconnected NCS system Sys_p which his parameters depend essentially on all subsystems. Besides, the responses of defective plant Y_{pf}(t) are controlled by centralized control: U(t) and decentralized controls: u_1(t) and u_2(t) in the presence of faulty sensor (see respectively figure5 and 6). The global and distributed outputs respectively Y_{pfg}(t) and Y_{pf}(t)are reconfigured where a change then it recovers the desired output Y_m(t) of reference model. In figure7, the errors between the outputs defective processus and his reference model towards zeros for centralized and decentralized adaptive controllers.

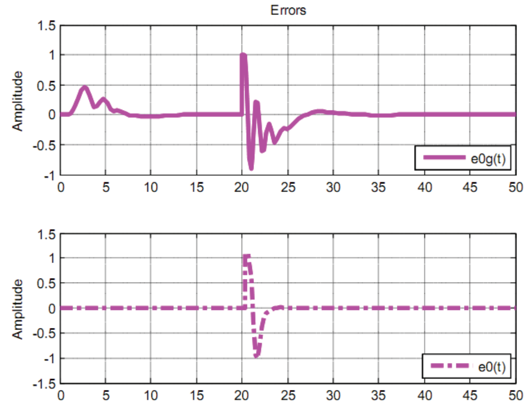

Figure 7: State errors

In the presence of additive defects, the accommodation of the N-interconnected and networked control subsystems is assured by the fault tolerant adaptive control based on reference model. We can note that the decentralized architecture of adaptive FTC implanted of an overall interconnected networked control system permits to build high performances and marvelous accommodation. The actual class of system may be robust to change all delay parameters. If the sum of delay τ overstepping the limited values, the processus cannot be stable. The adaptive fault tolerant controllers are based on updated controller parameterizations C_0^* and G_0^*. They are updated by some adaptive laws and they are designed to minimize the deviation of output caused by the fault f_s(t). Moreover, the figure8 illustrates simulation results of various trajectories (centralized and decentralized) controls.

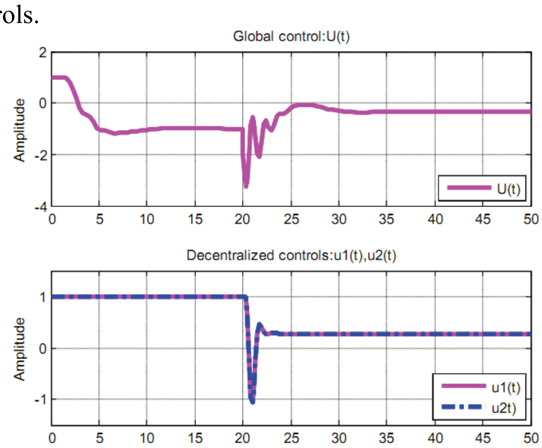

Figure 8: Trajectories of global and distributed controls

So, many strong points of the present fault tolerant adaptive control schemes in comparison with the existing techniques for two representations (centralized/decentralized) of INCSs are the following:

(i) they are two structures of large-scale system which differ from one another in the model used to represent the coupling between N-subsystems on which the controls are based;

(ii) sensor faulty dynamics are included in the adaptation loop and hence any on-line estimation parameters of overall system and N-interconnected subsystems will not cause significant of presence of sensor faults;

(iii) the present approach can be regarded as a generic one leading to different specific schemes that result from the choice of controller models of different degrees of complexity. There exists a tradeoff between models complexities and system performances for some tracking tasks. This can be used for the choice of appropriate fault tolerant adaptive control structures for desirable tasks;

(iv) the appropriate selection of decentralized techniques to be employed on N-interconnected subsystems distributed;

(v) a major point in the present development from the two architectures (centralized/decentralized) of controls that are high performances and marvelously reconfigurations of the distributed fault tolerant adaptive controls.

5. CONCLUSION

Model reference adaptive FTC implemented on interconnected and networked control system subject to compensate faulty sensor was studied in this paper. The main contributions include essentially:

1) Modeling NCSs subject to both access interactions and delay in presence of faulty sensors;

2) Determining different architectures (centralized and decentralize) of adaptive model reference controllers for N-interconnected and networked control subsystems.

A simulation example of three interconnected and networked control subsystems was studied to illustrate effectiveness of the proposed method.

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