A Robust Controller Configuration and Sensor Fault Tolerance of Complex System

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Abstract— **In large-scale system, the infinite dimension and complexities interconnection of N-subsystems are the major factors which deteriorate the overall system dynamic performance and potential overall system stability. Complex system which can decomposed in N-interconnected sub-systems is investigated in this paper. The continuous-time adaptive fault-tolerant control (FTC) and the quantitative feedback theory are used together to control the overall complex system with sensor failures. The global stability of overall system in the inner loop without affecting the nominal performance based on the generalized internal model control (GIMC) structure is studied. This existing technique is used to obtain the necessary global control performance in the outer loop and robustness as well. The simulations which are of evaluative example, are given to demonstrate that the centralized controller prove better reconfiguration of the overall system dynamic performance and global stability in presence of an additive sensor fault.**

I. INTRODUCTION

Significant progress in centralized and decentralized control design for various structures of system has been achieved by the use of various active fault-tolerant control (FTC)techniques. Then, the most large-scale plants in the industry have severe connection, complexity, infinite dimension, nonlinearity,..,which are difficult to design and control using complex systems. Growing demands for this system availability, reliability and survivability has prompted active research in fault-tolerant control [1]-[2]-[3]-[4]. Active fault-tolerant control approach (AFTC)is designed to accommodate component faults automatically by ensuring the overall system stability and acceptable level performance. However, there are very few studies concerning with the control of interconnected systems [5]-[6]-[7]. Also as it is known, the decentralized control of large-scale systems has been subject of recurring interest many applications in economic models, power systems, etc [6]-[9]-[10]. Then, it has shown the existence of interconnection terms usually becomes the source of global instability and deteriorates the performance of the overall system [7]-[9]. Nevertheless, purely robust control based FTC such as studied in [9]-[11] ensures robustness towards minor faults only; faults are modeled as very small perturbations on the system. It is not possible for a purely robust control structure to maintain high performance when faults are not present as they are designed using the worst case criterion.

Based on the IMC structure studied in [9]-[11], Campos-Delgado, Maruyama and Zhou have developed the generalized internal model based control (GIMC). Further demonstrations of the GIMC based FTC design and implementation can be found in [12]-[13]-[14]. The FTC structure that is proposed ensures the achievement of best performance objectives when faults and uncertainties are present.

The aim of this paper is to develop a robust centralized fault-tolerant control approaches for a particular class of complex system with some interconnections. In section II, the nature and identification parameters of complex system which can be decomposed into N-interconnected sub-systems are outlined and the the global robust FTC approach is explained. In the next section, an illustrative example is simulated to demonstrate the efficacy of the designed controllers in section II and main results are presented.

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II. PROBLEM FORMULATION

A. interconnected system

In literature, it exists three equivalent forms of certain class of large scale systems [4]-[5]-[9]-[15]:

*1-**Aggregate form**:* where the system structure is not specified.

*2-**Interconnected form**:* the interconnected form with arbitrary interconnection which reveals the system structure in its original form.

*3-**Block lower triangular form**:* this casts the original system into an interconnection of strongly connected components.

In the robust FTC of different class of such systems, we will find it some convenient and instructive to utilize the notion of global stability preserving interconnections [7]-[8]. Dynamic complex system (S) can be described by the ordinary differential equation:

$$(S)\begin{cases} \dot{X} = f(t,X,U) \\ Y = g(t,X,U) \end{cases} . \quad (1)$$

Where:

$t \in \mathbf{R}$ and $X \in \mathbf{R}^n$ represents the vector of state, $U \in \mathbf{R}^m$ represents the vector of input and $Y \in \mathbf{R}^q$ represents the vector of output.

Assume two functions f and g defined respectively as $f : \mathbf{R} \times^n \times^m \to \mathbf{R}^n$ and $g : \mathbf{R} \times \mathbf{R}^n \to \mathbf{R}^q$. The first function describes the dynamics of system and the second describes the observations of (S) to be defined and continuous on the domain. Moreover, using the problem formulation in (1), its solution exists for all initial conditions.

The complex system (S) described by (1) can be decomposed into N-interconnected sub-systems (S_i) described by the equation as follows[4]-[15]:

$$(S_i)\begin{cases} x_i = f_i(t,x_i,u_i) + f_i^{'}(t,x_i,u_i) \\ y_i = g_i(t,x_i,u_i) + g_i^{'}(t,x_i,u_i) \end{cases}. \quad (2)$$

In this new description of the system (S), the functions represent the dynamics of each isolated subsystem (S_i). $f_i\ and\ f_i^{'} : \mathbf{R}\times\mathbf{R}^{n_i}\times\mathbf{R}^{m_i}\rightarrow\mathbf{R}^{n_i}$ describes the dynamic interaction of (S_i) with the rest of the system (S). The function represents the observations at $(S_i)$from its local state variables. The function $g_i\ and\ g_i^{'} : \mathbf{R}\times\mathbf{R}^{n_i}\rightarrow\mathbf{R}^{q_i}$ represents the observations at (S_i) from the rest of the system (S). The system (S) has (p) inputs, (q) outputs and (n) state variables. In a similar way as in (2), the system (S) can be decomposed into N-interconnected subsystems (S_i) described by the equation:

$$(S_i):\begin{cases} \dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) \\ \qquad + \sum\limits_{j\neq i}\left(F_{ij}f_{ij}^{'}(t) + D_{ij}w_{ij}(t)\right) \\ y_i(t) = C_i x_i(t) + L_i v_i(t) + d_i(t) \quad ; i,j = 1,...,N \\ x_i(0) = \varphi_i(t) \end{cases} \quad (3)$$

And

$$\begin{cases} \sum\limits_{j\neq i}\left(F_{ij}f_{ij}^{'}(t) + D_{ij}w_{ij}(t)\right) \\ = \\ \sum\limits_{\substack{j=1\\ j\neq i}}^{N}\left(\bar{e}_{ij}^{xx}A_{ij}x_j(t) + \bar{e}_{ij}^{xu}B_{ij}u_j(t)\right) \\ L_i v_i = \sum\limits_{\substack{j=1\\ j\neq i}}^{N}\left(\bar{e}_{ij}^{yx}C_{ij}x_j(t)\right) \quad ; 1\leq i\leq N \end{cases}. \quad (4)$$

where A_i , B_i and C_i are, respectively $(n_i\times n_i)$, $(n_i\times q_i)$ and $(q_i\times n_i)$, constant matrices. d_i designs the external disturbances. The matrices represent the self parameters of i^{th} subsystem (S_i).

The matrices A_{ij} , B_{ij} and C_{ij} represent the interaction among the i^{th} subsystems due to the j^{th} subsystem.
The elements $\bar{e}_{ij}^{xx}, \bar{e}_{ij}^{xu}\ and\ \bar{e}_{ij}^{yx}$ are defined as follows:

$$\bar{e}_{ij}^{xx} = \begin{cases} 1\ , S_i\ can\ act\ on\ S_j \\ 0\ , S_i\ cannot\ act\ on\ S_j \end{cases} \quad (5)$$

$$\bar{e}_{ij}^{xu} = \begin{cases} 1\ , u_i\ can\ act\ on\ x_i \\ 0\ , u_i\ cannot\ act\ on\ x_i \end{cases}. \quad (6)$$

$$\bar{e}_{ij}^{yx} = \begin{cases} 1\ , x_i\ can\ act\ on\ y_i \\ 0\ , x_i\ cannot\ observed\ on\ y_i \end{cases} \quad (7)$$

Each subsystem (S_i) in (3) has (p_i) inputs, (q_i) outputs and (n_i) state variables such that:

$$n = \sum_{i=1}^{N} n_i, m = \sum_{i=1}^{N} m_i\ and\ q = \sum_{i=1}^{N} q_i. \quad (8)$$

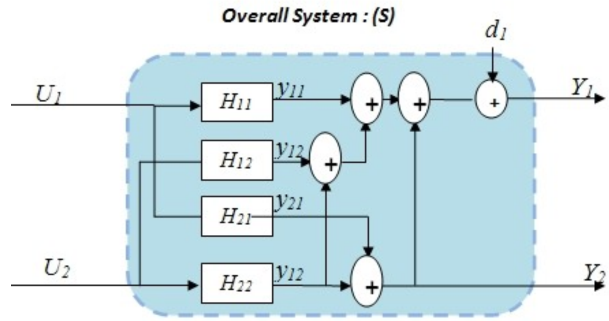

Fig. 1. Internal structure of two interconnected sub-systems

For linear time invariant lumped systems, (1) can be described by a set of equations of the form:

$$(S)\begin{cases} \dot{X}(t) = AX(t) + BU(t) \\ Y(t) = CX(t) + d(t) \end{cases} \quad (9)$$

where A, B and C are, respectively $(n\times n)$, $(n\times q)$ and $(q\times n)$.

A state space rational proper transfer function is denoted by:

$$H(s) = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = C(sI-A)^{-1}B + D. \quad (10)$$

Moreover, using the global input vector *U(s)* and global output vector *Y(s)* parametres, the global transfer function of overall interconnected system can be defined as:

$$H(s) = \frac{Y(s)}{U(s)} \quad (11)$$

Hence, let the global transfer function H be a block matrix as follows:

$$H(s) = \begin{bmatrix} H_{11}(s) & H_{12}(s) & \cdots & H_{1N}(s) \\ H_{21}(s) & H_{22}(s) & \cdots & H_{2N}(s) \\ \vdots & \vdots & \cdots & \vdots \\ H_{N1}(s) & H_{N2}(s) & \cdots & H_{NN}(s) \end{bmatrix} \quad (12)$$

A demonstrative case is studied. Denote N=2, we consider a system *(S)* consisting of two interconnected subsystems. they have two inputs (U_1,U_2) and two outputs(Y_1,Y_2). The internal structure of all interconnections between two subsystems (S_1) and (S_2) can be represented in fig.1.

The global transfer function of overall system decomposed into two interconnected subsystems (see fig.1) is defined as:

$$H(s) = \begin{bmatrix} H_{11}(s) + H_{21}(s) & H_{12}(s) + H_{21}(s) + H_{22}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} \quad (13)$$

The system can be separated into two single-input and single-output (SISO). Then, two distributed interconnected subsystems (S_1) and (S_2) have two distributed transfer functions $H_1(s)$ and $H_2(s)$ respectively [10].

On the one hand, the first interconnected subsystem (S_1) has the transfer function as follows:

$$H_1(s) = H_{11}(s) + H_{21}(s) - \frac{(H_{12}(s) + H_{21}(s) + H_{22}(s))\,H_{21}(s)}{H_{22}(s)}. \quad (14)$$

Then, the second transfer function characterizing the second interconnected subsystem (S_2) is described by:

$$H_2(s) = H_{22}(s) - \frac{(H_{12}(s) + H_{21}(s) + H_{22}(s))\,H_{12}(s)}{H_{11}(s) + H_{21}(s)}. \quad (15)$$

B. Sensor fault defined

Sensor fault symptoms can be observed as measurements that are unavailable, incorrect or unusually noisy. These faults may occur individually or concurrently or simultaneously, resulting in total system failure or deterioration in performance. Significant information about the influence of faults on a process cannot be known without the inclusion of its model in the design. Additive faults provide a suitable framework for sensor faults and are modeled as additional input signal to one or all interconnected sub-systems [4]-[5].

$$y_i(s) = C_i x_i(s) + D_i u_i(s) + d_i(t) + f_{si}(s) \quad (16)$$

where $f_{si}(t) \in \mathbf{R}^m$ denotes sensor faults.
Hence, using (11) and (16) the global defective output of overall system is given:

$$Y_f(s) = H_f(s)\,U_f(s) \quad (17)$$

Due to the existence of fault represented by $f_{si}(s)$ on i^{th} interconnected sub-system a conventional centralized controller cannot usually satisfy required and optimal performance. Then, it becomes the source of instability and deteriorate the performance of the overall system. A sensor fault compensating centralized controller can be introduced to augment a nominal centralized controller designed for best performance. However, in order to render the fault compensating to be well defined and proper the transfer matrix representation from $f_{si}(s)$ to controller global output, the global input U_f must exists and is proper.

Therefore, the additive sensor fault is defined as:

$$f_{si}(s) = F(s)\,f'_{si}(s) \quad (18)$$

where $F(s)$ and $f'_{si}(s)$ are respectively the appropriate use weight and unknown input which can be normalized and transformed into the physical input $f_{si}(s)$.

Consideration of such sensor fault models has been shown to be suitable for use in formulation the FTC objectives for rejection of sensor faults as an optimization problem. The presence of i^{th} sensor faults and uncertainty vectors defined in the previous section can be reflected by a global fault indicating residual since a filtered estimation can be obtained via coprime factorization of the plant model (13) can define as:

$$H_f(s) = \tilde{M}_f^{-1}(s)\,\tilde{N}_f^{-1}(s) \quad (19)$$

Hence, from (17), (15) and (19), the i^{th} sensor fault signal denoted by $f_{si}(s)$ can be defined as:

$$\begin{aligned} f_{si}(s) &= \tilde{N}_f(s)\,U_f(s) - \tilde{M}_f^{-1}(s)\left[Y_f(s)\right] \\ &= -\tilde{M}^{-1}(s)\,F(s)\,f'_{si}(s) \\ &= -\tilde{M}^{-1}(s)\,f_{si}(s) \end{aligned} \quad (20)$$

Here $f_{si}(s)$ reflects the presence of faults and uncertainty.

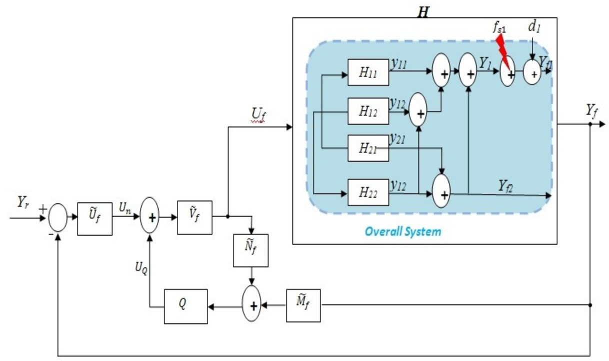

Fig. 2. Bloc diagram of global controller compensating sensor fault

Then, the perturbation caused can be minimized by centralized control action due to the nominal global controller and the compensating global controller.

C. Intergrading generalized controller

The global control vector can be expressed as follows:

$$U_f(s) = U_n(s) + U_Q(s) \quad (21)$$

where $U_n(s)$ and $U_Q(s)$ design respectively the nominal centralized controller and the sensor fault global compensator output.
Nominal global controller is described by:

$$U_n(s) = K_0(s)\,e(s) \quad (22)$$

And the global sensor fault compensator is given by:

$$U_Q(s) = -Q(s)\,\tilde{M}_f(s)\,f_{si}(s) \quad (23)$$

Thus, Youla has been done in the field of a particularize parameter which can offer an adequate architecture (fig.2) for the design of an AFTC law. It is called the parameter Youla and it is denoted by Q. This parametrization allows the description of all the correctors stabilizing the overall interconnected system and satisfying a desirable performance level. The idea is to elaborate a global nominal corrector and the parametrization of Youla to parameterize it, in order to make it robust and to respect a class of predetermined defects. The later are the considered as model uncertainties that f_{si} means an additive defect. To formalize the idea of an AFTC using a GIMC structure, we consider the global transfer function H of the operational overall interconnected system and K_0 as a global controller stabilizing it. Hence, $\tilde{U}, \tilde{V} \tilde{M} and \tilde{N}$ are the left factorizations coprimes. So, the central regulator has the following form [12]-[13]-[14]

$$K_0(s) = \tilde{V}_f^{-1}(s)\,\tilde{U}_f(s) \quad (24)$$

Any corrector K stabilizing H deducing from the parameter Youla and left coprimes factorizations can be take. The matrix transfer Q is considered as the tolerant control law to the disturbances. This idea which is cited can be represented and seen in fig.2.

The particular architecture which was described by fig.2 is called a Generalized Internal Model Control structure (GIMC). If $Q=0$, we find K_0. This centralized controller stabilizes the nominal transfer matrix H while ensuring some desired closed loop performances.

The Youla parameter satisfies the following relation:

$$Q(s) = -\tilde{U}_f(s)\tilde{M}_f^{-1}(s) \tag{25}$$

The Youla parameter (26) can be synthesized either starting from the objectives of diagnosis or starting from the objectives of control, or by managing a com promise between the performances specifications in control and diagnosis. In this case, we are interested in using the Youla parametrization of which has been taken again by Delgado to accommodate the failures sensors. The tolerant control law to the disturbances (Q) is considered as an optimal solution to the optimization criteria using left coprime factorization of H. Indeed, for this choice of Q, the last condition is null.

D. Fault indicating residuals

Denote by *e(s)* the error from global feedback and by *r(s)* the global residual generator for complex system. They design the input demands. They are described as follows:

$$\begin{cases} e(s) = r(s) - H_f(s)U_f(s) - f_{si}(s) \\ r(s) = \tilde{N}_f(s)U_f(s) - \tilde{M}_f(s)Y_f(s) \end{cases} \tag{26}$$

The centralized control law $U_f(t)$(21) is then written as a function of the residual generator:

$$U_f(s) = \tilde{V}_f(s)^{-1}\left(\tilde{U}_f(s)e(s) + r(s)\right) \tag{27}$$

Sometimes, it is not desirable to have the compensation signal active all the time. Youla parameter is defined by equation (26)which guarantees neither the robustness against model errors, nor the robustness against an additive fault. To resolve this problem, it is proposed to adopt a FTC structure where the compensation signal is added to the nominal control signal because of the fault detection and location. The activation of fault tolerant control strategy is carried out using commutation logic.

III. EXAMPLE STUDY

To illustrate the mentioned active robust FTC technique, the application to the overall system which is decomposed into two interconnected subsystems (S_1) and (S_2), is presented. The internal structure of the overall interconnected system is shown in fig.2. Moreover, the both interconnected sub-system dynamics model are defined as:

$$H_1(s) = H_2(s) = \frac{5}{0.4s^2 + 1.85s + 1}\begin{bmatrix} 2 & 3 \\ 1 & 1 \end{bmatrix}. \tag{28}$$

where:
$\tilde{M}_1(s) = \frac{s^2+4.625s+2.5}{s^2+5.25s+17.89}$;
$\tilde{N}_1(s) = \frac{12.5}{s^2+5.25s+17.89}$.
$\tilde{V}_1(s) = \tilde{V}_1^{-1}(s) = 1$ *and* $\tilde{U}_1(s) = 1.26$.

The aim of this section is to verify if the proposed global controller can make two-interconnected subsystems near optimal sensing performances and marvelous accommodation

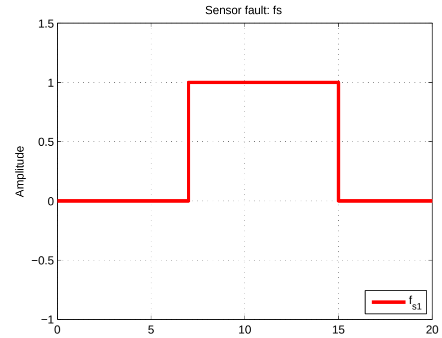

Fig. 3. Curve of fault

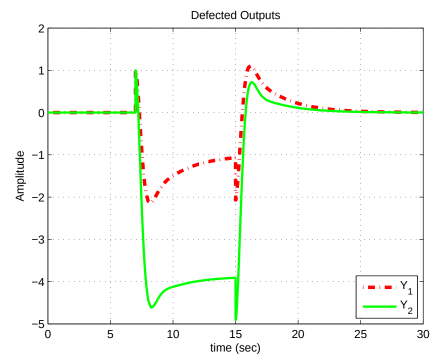

Fig. 4. Output signals of overall system

in presence of sensor fault. So, our objective is to guarantee the global stability of overall interconnected system consisting of two subsystems with some interconnections. The traction of the global reference trajectory $(y_r(s) = 0)$ under faulty parameters and with external disturbances output is recommended.
A signa fault $f_{si}(s)$, i=1,2, which is represented in fig.2 was generated only on the first sub-system which is coupled with the second subsystem. Figure 3 shows the signal fault where the additive sensor fault attacked the first subsystem (S_1) coupled with another subsystem (S_2) at $3 \leq t \leq 10sec$. The sensor fault has amplitude 1.

So, to speak the defective first subsystem (S_{f1}) coupled with the second subsystem, the first relationship output is given as follows:

$$y_{f1}(s) = y_1(s) + d_1(s) + f_{s1}(s) \tag{29}$$

The second faulty output can be modeled by:

$$y_{f2}(s) = y_2(s). \tag{30}$$

A. Main results and interpretations

This section gives a brief response curves of defective overall system (S_f) that is decomposing into two defective interconnected subsystems (S_{f1}) and (S_{f2}). All system responses are shown in fig.4. They track the desired reference

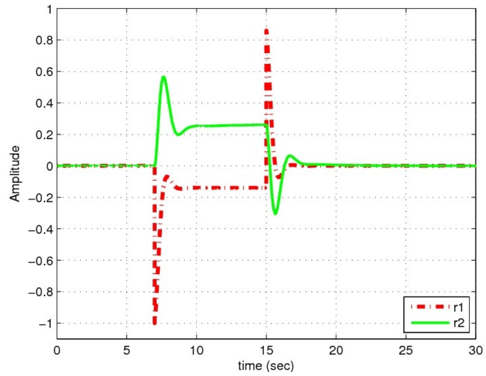

Fig. 5. Residual signals

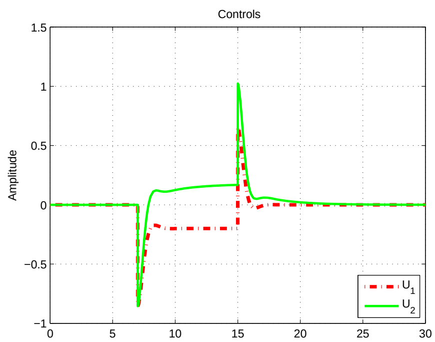

Fig. 6. Control signals

trajectory $(y_r(s) = 0)$ as $t \to \infty$ and have two deviations at t=3sec and t=10sec signaling the presence of $f_{s1}(s)$.

Obviously, the defective second output subsystem (S_{f2}), also, has two picks at t=3sec and t=10sec. However, the overall interconnected system has high accommodation against sensor failure. Furthermore, for this type of fault (see fig.3), the main problem is fault detection, since according to the faulty measurement, the all residual will take more time to overcome the detection threshold as shown in fig.5.

However, the robust FTC algorithm can also compensate this additive sensor fault. Finally, fig.6 shows the vector controls trajectories. Hence, the complex system without compensation is unstable. But, the compensated overall interconnected system is able to recover its global stability and the reference input performance is tracking.

IV. CONCLUSION

In this paper, a robust centralized fault tolerant control methodology is developed for a particular class of complex system which can be decomposed into N-subsystems with some interconnections. The robust basic approach is based on a rigorous GIMC structure. Only one sensor of an i^{th} interconnected sub-system was attacked by an additive fault. The other sub-system was influenced by the presence of sensor failure. To demonstrate the capability of the proposed robust global controller configuration, we apply it to maintain an availability and an acceptable level of global performance and global stability for the overall system constituting of two interconnected sub-systems in presence of unknown deteriorated sensor condition. The simulation results have shown the effectiveness of the proposed robust FTC design method.

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