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A New Decentralized Fault Tolerant Control Strategy and the Fault Accomodation of Coupled Drives

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***Abstract*—This paper presented a novel decentralized fault tolerant control strategy for the control of linear multivariable processes. The multiple model based fault tolerant method is used to improve system performance (under model uncertainty and slow variation) and implement active fault tolerant control. In the mean time, we extended the decentralized unconditional stable control to multiple model cases to implement passive fault (partial failure of actuator or sensor) tolerant control under partially isolated failures. This strategy was applied in the fault accommodation of coupled drives.**

Keywords-component; Fault tolerant control; Unconditional stability; Coupled drives; Multiple model based control;

I. INTRODUCTION

Modern control systems are becoming increasingly complex with more and more demanding performance goals [1]. These complex systems must have the capability for fault tolerant in order to operate successfully over long periods of time. Such systems require fault detection, isolation and controller reconfiguration so as to maintain adequate levels of performance with one or more sensor, actuator, and/or component failures, or a combination of these events.

Fault-tolerant control (FTC) is a multi-disciplinary area of research in which a number of new research areas are emerging [2]. Fault tolerance can be obtained by employing fault detection and on-line diagnosis, and sending a discrete event signal when a fault is detected to a supervisor-agent, who in turn activates accommodation actions.

Papers [1-7] in the fault tolerant control area mainly concentrate on two issues: fault detection and isolation (FDI) [3] and controller accommodation or reconfiguration [4]. They mainly combine the estimation and prediction methods (to implement fault detection and isolation) with some adaptive or robust methods (to fulfill controller accommodation or reconfiguration).

Most papers apply multiple model technique to cope with faults. Each fault mode is described by a corresponding model. Then, the fault detection and isolation problem becomes a model identification or determination problem.

Paper [5] applied a linear perturbation stochastic state model, with an uncertainty parameter vector (corresponding to failure status) affecting the matrices defining the structure of the model. It also assumed that the parameters can take on only discrete time values. A bank of K separate Kalman filters is designed to correspond to the set of possible parameter values. Based on the observed characteristics of the residuals in these K filters, the conditional probabilities of each discrete parameter value being "correct" are evaluated iteratively. A separate set of LQG controller is associated with each elemental filter in the bank. The overall control action is computed as a convex combination of the outputs of the different controllers.

One disadvantage for the method presented in [5] is when the model in effect is not contained in the model set, the control action does not guarantee optimality of the performance objective. Another is the design of the bank of Kalman filters for all possible failure modes is almost impossible in practice.

Paper [8] presented a hybrid active and passive fault tolerant control approach, which can effectively decreased the number of Kalman filters required for FDI.

All of the above FTC approach is based on FDI. FDI method is relatively practical in use, but the only drawback is the determination of the confidence region. In general, perfect decoupling of residuals from uncertainties is only possible in a limited number of model parameters, and the wrong selection of model will leads to unpredicted results. In this paper, a similar estimation method is developed based on the calculation of the residual. However, we used a more cautious model selective rule for model determination to avoid wrong selection of model. Instead of isolating the failure, we reduce the set of failure modes by screen out impossible failures identified. This approach can therefore lessen the requirement of failure isolation tasks. However, fault accommodation becomes harder. This paper extended the decentralized unconditional stable control to multiple model cases to accommodate partially isolated failures. We use the control of coupled drives to illustrate the design of decentralized unconditional stable control for several failure modes.

This paper is organized as follows. Section II introduces the proposed method. We illustrate this method by the decentralize control of couple drives in Section III. Section IV concludes the paper.

II. PROPOSED FTC APPROACH

A. Some notations and concepts

As the FTC is a multi-disciplinary area, before introduce our method, it is necessary to clarify some notations and concepts.

In [4], the concept of *active fault tolerant control system* is defined as: A fault-tolerant system where faults are explicitly detected and accommodated. The *passive fault-tolerant system* is a fault tolerant system where fault are not explicitly detected and accommodated, but the controller is designed to be insensitive to a certain restricted set of faults.

Paper [3] uses *explicit fault tolerant control* and *implicit fault tolerant control* to name *active fault tolerant control* and *passive fault tolerant control*. According to these definitions, the decentralized unconditional stable controller belongs to *passive fault tolerant control system* or *implicit fault tolerant control.*

Residual is defined as to generate fault information based on deviation between measurements and model based computations [4].

Hardware redundancy or physical redundancy means to accomplish a given function by using more than one independent instrument. Analytical redundancy refers to determine a variable by using two or more, but not necessarily identical ways where one way uses a mathematical process model in analytical form.

B. Model set

This paper assumes that the model set is given empirically. Both the model uncertainty (such as, the process variant and un-modeled dynamics) and failure modes are covered by the given set of models.

In this study, we only consider linear time invariant systems described as follows:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases}$$

We consider actuator faults and/or sensor faults. These failure modes can be treated as in [1]. Total actuator failures may be modeled by making zero(s) the appropriate column(s) of the B matrix. For total sensor failures one needs to annihilate the appropriate row(s) of the C matrix. Partial actuator or sensor failures are modeled by multiplying the appropriate column (row) of the B (or C) matrix by a scaling factor. For example, a partial 40% sensor failure is modeled by multiplying the corresponding row of the C matrix by 0.4.

The unconditional stable controller can guarantee stability and offset free tracking for partial actuator/sensor failure. Thus, only total actuator/sensor failure need to be considered as a fault and control reconfiguration is needed.

C. Multi-estimator design and new model decision-making rule

This paper applies residual generator as a tools to select a correct model set. The residual generator is a linear dynamic algorithm. Its generic form is

$$R(s) = Y(s) - M(s)U(s)$$

Where, *R(s)*, *Y(s)* and *U(s)* are the Laplace form of the residual signal, process output and control effort respectively. *M(s)* is the designed residual generator. Specifically, the optimal state estimation methods are employed to minimize the residuals caused by noises and the estimation errors of initial state values as stated in [8] (Kalman filter based residual generator).

Ideally, the residual information is sufficient to determine a precise model for the plant. However, the presence of disturbances, noise and modeling errors causes the residuals to become non-zero even for the correct selected model.

According to [7], there is no algorithm which is robust under arbitrary model error conditions. Although some robust active residual generators are reported [9][10], perfect decoupling of residuals from uncertainties is only possible in a limited number of model parameters. Paper [2] proposed a robust passive residual generator, which enhances the robustness of model selection at the decision-making stage. A tolerant interval is predetermined according to the uncertainty of parametric model uncertainty. Only when the residual value is outside the interval, the model update is needed.

However, we adopted a more cautions robust passive residual generator. At the decision-making stage, only worst model is screen out based on the residual values at first because of lacking of information. Then, gradually the model set is contracted as more wrong model has been ruled out. However, the active residual generator can also be used simultaneously when information is accurate enough to determine a single model.

D. Fault accomodation

When a decentralized controller is used, control system stability under the above circumstances can be achieved if the controller maintains closed-loop stability when one or more of its output channels are arbitrarily detuned or switched off. Closed-loop stability under this condition is called decentralized unconditional stability (DUS). For decentralized designs [11], another important issue is *decentralized integral controllability* (DIC). DIC analysis determines whether a multivariable plant can be stabilized by multi-loop controllers, whether the controller can have integral action to achieve offset free control, and whether the closed-loop system will remain stable when any subset of loops is detuned or taken out of service.

After partially identified the failure modes, the key issue for fault accommodation is to design Decentralized Unconditional Stable integral controller for several multivariable models simultaneously. We provide some definitions to clarify our discussions.

Definition 1 (Simultaneously DIC)

For a set of stable linear systems G_i ($1 \le i \le n$), if there exists a decentralized integral controller C such that the closed loop system of ($G_i, -C$) is decentralized unconditional stable for $1 \le i \le n$, then the set of stable linear systems is said to be Simultaneously Decentralized Integral Controllable (SDIC).

Definition 2 (Simultaneously DUSC)

For a set of stable linear systems G_i ($1 \le i \le n$), if there exists a decentralized controller C such that the closed loop system of ($G_i, -C$) is decentralized unconditional stable for $1 \le i \le n$, then the set of stable linear systems is said to be Simultaneously Decentralized Integral Controllable (SDUSC).

We provide the following two lemmas to determine the existence of a DIC controller for a set of linear stable systems:

Lemma 1 (Necessary and Sufficient Conditions for SDIC)

A set of stable linear systems G_i ($1 \le i \le n$) is SDIC if and only if each linear system G_i is DIC.

Lemma 2 (Simultaneously Decentralized Integral Unconditional Stable Controller (SDIUSC))

Assume that a set of stable linear system ϕ is a subset of another set of stable linear system φ (i.e. $\phi \subseteq \varphi$), if a decentralized integral controller C can simultaneously unconditionally stabilize the set of linear system φ, then, the controller C can also simultaneously unconditional stabilize the set of linear system ϕ.

Although Lemma 1 and 2 are obvious, they imply two important facts. The first one is that the condition of existence of SDIC is rather modest. It only needs that every system in the set is DIC. This implies our method can be used to handle broad decentralized fault tolerant control problems.

Another is that the smaller of the set size, the more freedom to design SDIUSC controllers. In other words, if the size of a set of linear system reduces, then a SDIUSC controller with better performance can be found. This supports the model screening out rule propose in last subsection.

Actually, we can apply the passivity index method [12] to design a SDIUSC controller for a set of linear systems. The only difference is for each frequency, all the passivity index of each G_i ($1 \le i \le n$) need to be calculated, and the lowest one is regarded as the passivity index in this frequency.

The simultaneously decentralized integral control requires all the under controlled systems satisfy DIC condition. One of the necessary conditions requires the steady state gain matrix of the linear multivariable system is nonsingular. However, this condition is often violated under serve failure scenarios. Instead of design a SDIUSC controller, we can design a SDUSC controller, which only requires the systems under controlled are asymptotically stable. Then, steady state tracking error will appear as we have to give up integral action to ensure stability.

III. FAULT ACCOMODATION FOR A COUPLED DRIVES

Figure 1. Coupled drive system.

Figure 1 shows a coupled drive system. The standard system has two drive motors. These drives operate together to control the speed of a continuous flexible belt and that goes round pulleys on the drive motor shafts and a jockey pulley. The jockey pulley is mounted on a swinging arm that is supported by a spring. Regulation the tension and speed of coupled drive systems are very commonly encountered in the manufacture of textiles, paper, wire, and plastic films.

The nominal coupled drive system can be model as follows (See www.control-systems-principles.co.uk):

$$G_0: \begin{bmatrix} \omega \\ x \end{bmatrix} = \begin{bmatrix} \frac{1}{0.3s+1} & \frac{1}{0.3s+1} \\ \frac{185600}{(s^2+11s+150)(s^2+1.6s+800)} & \frac{-185600}{(s^2+11s+150)(s^2+1.6s+800)} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Where, u_1 and u_2 are the voltages exerted on the two motors. ω is the angular velocity and x the tension measurement.

For nominal system, it is assumed that the two drives are exactly symmetry. However, this assumption is usually invalid as it is almost impossible to build two identical drives. Moreover, the electrical circuits of the two drivers as well as the sensors of tension and velocity often exhibit malfunctions or failures when working environments change from time to time.

We consider two serve failure cases:

a) Drive 1 totally failed. The corresponding model is shown as follows:

$$G_1: \begin{bmatrix} \omega \\ x \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{0.3s+1} \\ 0 & \frac{-185600}{(s^2+11s+150)(s^2+1.6s+800)} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}.$$

b) Drive 2 totally failed. The corresponding model is shown as follows:

$$G_2: \begin{bmatrix} \omega \\ x \end{bmatrix} = \begin{bmatrix} \frac{1}{0.3s+1} & 0 \\ \frac{185600}{(s^2+11s+150)(s^2+1.6s+800)} & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}.$$

Before we design decentralized controller, a decoupling compensator is designed as:

$$D = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}.$$

After decoupling, a classical integral controller for the normal model is designed as follows (See www.control-systems-principles.co.uk):

$$C_0 = \begin{bmatrix} \frac{s+5}{s} & 0 \\ 0 & \frac{-1}{s(0.4s+1)} \end{bmatrix}.$$

A decentralized integral controller is also designed for the normal system G_0 based on passification approach:

$$C_{G_0} = \begin{bmatrix} \frac{(s+3.322)(s^2+11s+150)(s^2+1.6s+800)}{s(s^2+15.02s+189.1)(s^2+1.817s+793.3)} & 0 \\ 0 & \frac{-1.2823(s+3.322)(s^2+11s+150)(s^2+1.6s+800)}{s(s+214.3)(s+4.06)(s^2+12.42s+270.4)} \end{bmatrix}$$

.

Control results for healthy system G_0 are shown in Figure 2.

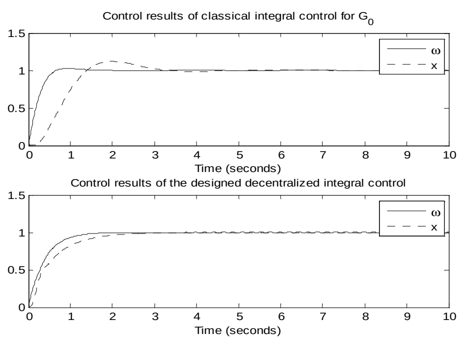

Figure 2. Decentralized integral control and classical integral control for G_0.

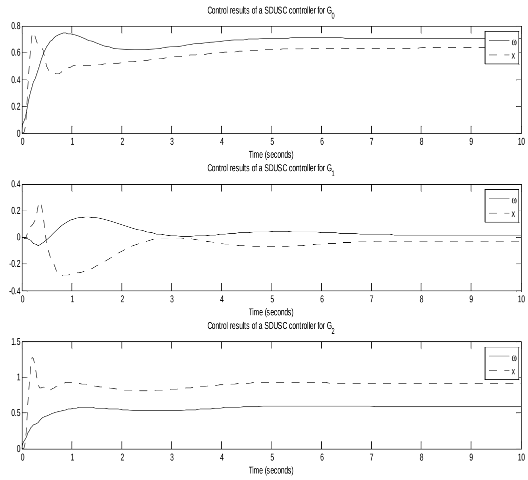

Figure 3. Control results of a Simultaneously Decentralized Unconditional Stable Controller for the model set *{G0, G1, G2}*.

These nominal controllers C_0 and C_{G0} cannot be used for failure modes a) and b) as unacceptable overshoot may damage the system. It also needs to be mentioned that the decentralized integral controller cannot be designed for failure modes a) and b) because their steady state gain matrix is singular. Therefore, instead of design an SDIUSC controller, we designed a SDUSC controller for nominal model as well as for two failure modes *({G0, G1, G2})*. The control results are shown in Figure 3. Although this controller can avoid harmful overshot for all models, the responses is quite slow.

We can design SDUSC controllers for the model sets (*{G0, G1} and {G0, G2}*) as well. When the model set reduced, its corresponding SDUSC or SDIUSC controller can be applied. Then, better performance can be obtained while guaranteeing the safety of the system.

IV. Conclusion

This paper presented a new fault tolerant control strategy for multivariable linear systems. We simplified the design of Fault Detection and Isolation part. To accommodate partial identified failures, Simultaneously Decentralized Integral Unconditional Stable Controllers (SDIUSC) are designed and employed for different failure scenarios. This method is illustrated by the design of a fault tolerant controller of the coupled drive system.

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