Expert Systems with Applications 39 (2012) 10630–10638

Contents lists available at SciVerse ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Fault tolerant control using a fuzzy predictive approach

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ARTICLE INFO

Keywords:
Fault tolerant control
Fault detection
Fault isolation
Fuzzy decision making
Fuzzy optimization
Model predictive control

ABSTRACT

This paper proposes the application of fault-tolerant control (FTC) using fuzzy predictive control. The FTC approach is based on two steps, fault detection and isolation (FDI) and fault accommodation. The fault detection is performed by a model-based approach using fuzzy modeling and fault isolation uses a fuzzy decision making approach. The information obtained on the FDI step is used to select the model to be used in fault accommodation, in a model predictive control (MPC) scheme. The fault accommodation is performed with one fuzzy model for each identified fault. The FTC scheme is used to accommodate the faults of two systems a container gantry crane and three tank benchmark system. The fuzzy FTC scheme proposed in this paper was able to detect, isolate and accommodate correctly the considered faults of both systems.

1. Introduction

Complexity of technical processes is increasing continuously. One consequence of this increase is that safety the reliability become important system requirements. The complexity of these systems increases when the fault probability increases. This is the main reason why control systems include automatic supervision of process control to detect and isolate faults as early as possible and to perform fault accommodation.

FTC can be performed by passive methods or by active methods. Passive methods make use of robust control techniques to ensure that a closed-loop system remains insensitive to certain faults using constant controller parameters and without use of on-line fault information (Zhang & Jiang, 1985). In active methods, a new control system is redesigned using desirable properties of performance and robustness in the system without faults. Active fault-tolerant controllers are generally variable in their structure. Active approaches are divided into two main types of methods: projection based methods and on-line automatic controller redesign methods (Patton, 1997). The reconfiguration includes the selection of a new control configuration where alternative input and output signals are used (Blanke, Kinnaert, Lunze, & Staroswiecki, 2003). On the other hand, fault accommodation adapts the controller parameters to the dynamical properties of the faulty plant. A simple but well established way of fault accommodation is based on predesigned controllers, each of which selected off-line for a specific fault (Blanke et al., 2003). Fault accommodation involves the detection and isolation of faults, and taking appropriate control actions that eliminate or reduce the effect of faults and maintains the control.

The use of model predictive control to deal with fault accommodation is relatively natural and straightforward, considering the representation of both faults and control objectives (Maciejowski & Jones, 2003). MPC with additional flexibility is obtained using fuzzy sets in the objective function. The fuzzy sets theory provides ways of representing and dealing with flexible or soft criteria. The fuzzy objective function used in MPC includes goals and the constraints. The optimal trade-off amongst fuzzy goals and fuzzy constraints is determined by maximizing simultaneously the satisfaction of the optimization goals and the constraints (Sousa & Kaymak, 2001).

The FDI approach used in this paper uses one fuzzy model representing the normal state of the system and one fuzzy model for each fault that can occur in a given system. The faults are detected and isolated based on these fuzzy models (Mendonça, Sousa, & Sá da Costa, 2009). A fuzzy decision making (FDM) approach is used to isolate the faults. When a fault is isolated, fault accommodation is performed by using the respective faulty model. This paper proposes a fault tolerant control scheme, where the faulty model is used in a fuzzy MPC scheme. This control technique can be a highly efficient approach to perform fault accommodation (Gopinathan, Boskovic, Mehra, & Rago, 1998).

This paper is organized as follows. Next section presents fault tolerant control. The architecture for fault tolerant control proposed in this paper is presented in Section 3. Predictive control is presented in Section 4. This paper presents two application examples, the container gantry crane in Section 5 and the three tank benchmark process in Section 6. Finally, some conclusions are drawn in Section 7.

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http://dx.doi.org/10.1016/j.eswa.2012.02.094

2. Fault tolerant control

FTC can be motivated by different purposes, as the improvement of safety and efficiency in industrial processes. The main design challenges of FTC are: the number of possible faults and their diagnosability; the system reconfigurability, and the global stability of the system (Blanke, Frei, Kraus, Patton, & Staroswiecki, 2000).

2.1. State-of-art

Fault tolerant control can be classified into two types: passive approaches (Chen & Patton, 1999) and active approaches (Steffen, 2005).

Active fault tolerant control approach uses the FDI information to make the on-line controller reconfiguration or model selection (Chandler, Pachter, & Mears, 1995). In Patton and Klinkhieo (2009), a new approach to fault compensation for FTC using fault estimation is presented, where the faults acting in a dynamic system are estimated and compensated within an adaptive control scheme with required stability and performance robustness. The development of a novel FTC design method is presented in Guenaba, Webera, Theilliola, and Zhangb (2011), which incorporates both reliability and dynamic performance of the faulty system in the design of a FTC. Another possible approach is to use all the information given by FDI to improve the ability of on-line controller reconfiguration (Polycarpou & Helmicki, 1995).

The fuzzy logic approach in FTC is used in Lopez-Toribio, Patton, and Daley (2000) where Takagi–Sugeno (TS) fuzzy models are used in fault tolerant control of non-linear systems. In Ichtev, Hellendoorn, Babuška, and Mollov (2002), multiple TS fuzzy models are used in fault tolerant model predictive control. When MPC is used in FTC, some faults can be accommodate modifying the constraints in the MPC problem definition (Maciejowski, 2002). The use of MPC increases the degree of fault tolerance under certain conditions, when the fault is not detected. Thus, MPC in fault tolerant control provides a suitable implementation architecture and increases the system capability to accommodate the faults.

In order to overcome the limitations of conventional control, new controllers are being used which are capable of tolerating component malfunctions. Complex control applications require a capability for accommodating faults in the controlled industrial process. Fault accommodation involves the detection and isolation of faults, and taking appropriate control actions that eliminate or reduce the effect of the faults and maintains the control. The method used in this paper is an active approach.

2.2. FDI in fault tolerant control

A system that includes the capacity of detecting, isolating and identifying faults is called a fault diagnosis and isolation system (Chen & Patton, 1999). During the years, many research has been carried out using analytical approaches, based on quantitative models. The idea is to generate signals that reflect inconsistencies between normal and faulty system operation, and detect and isolate the faults. Such signals, the residuals, are usually generated using analytical approaches, such as observers, parameter estimation or parity equations. Early detection and isolation of abrupt and incipient faults can be achieved using a model-based approach, which processes all measured variables, using either qualitative or quantitative modeling. The use of fuzzy logic for fault detection and isolation in industrial processes is presented in Koscielny and Syfertm (2003). Optimized fuzzy models have been used with success in model based FDI (Mendonça et al., 2009).

The use of FDI in fault tolerant control is very important in the active way of achieving fault-tolerance, by detect and isolate the faults. After the fault indication by FDI, the system can then be reconfigured or restructured. In some cases, a pre-calculated controller will be activated, or the parameters of the controller will be changed according the real time diagnostic provided by the FDI. Next section presents the architecture of FTC proposed in this paper.

3. Architecture for fault tolerant control

This paper proposes a simple architecture for fault tolerant control. This approach is based on two steps: the first performs fault detection and isolation, and the second performs fault accommodation. The two steps are depicted in Fig. 1, and are denoted as FDI and FTC.

3.1. Fault detection and isolation

The fault detection and isolation approach is showed in Fig. 1 in the block called FDI. In this FDI approach, the multidimensional input, $\mathbf{u}$, of the system enters both the process and a model (observer) in normal operation. The vector of residuals $\boldsymbol{\varepsilon}$ is defined as

$$\boldsymbol{\varepsilon} = \mathbf{y} - \hat{\mathbf{y}}, \tag{1}$$

where $\mathbf{y}$ is the output of the system and $\hat{\mathbf{y}}$ is the output of the model in normal operation. When any component of ε is bigger than a certain threshold, the system detects faults. In this case, n observers (models), one for each fault, are activated, and n vectors of residuals are computed. Each residual i, with $i = 1,\ldots,n$, is computed as

$$\boldsymbol{\varepsilon}_{\mathbf{F}_i} = \mathbf{y} - \hat{\mathbf{y}}_{\mathbf{F}_i}, \tag{2}$$

where $\hat{\mathbf{y}}_{\mathrm{F}_i}$ is the output of the observer for the fault i. The residuals $\varepsilon_{\mathrm{F}_1},\ldots,\varepsilon_{\mathrm{F}_n}$ are evaluated, and the fault or faults detected are the outputs of the FDI system. The fault isolation is performed by evaluating *fuzzy decision factors*, which are built based on residuals. The fuzzy fault isolation used in this paper is based on fuzzy decision making (FDM) (Mendonça et al., 2009; Mendonça, Sousa, & Sá da Costa, 2006b). In this approach, a membership function $\mu_{\varepsilon_{ij}}$ is derived for each residual ε_{ij}. The membership functions used in this paper are trapezoidal because they revealed to be the most appropriate to describe the residuals in a simple and effective way. The membership functions spread is obtained experimentally based on the maximum and minimum variations of the residuals. The core of the membership functions indicates the possible isolation of a fault, i.e. if ε_{ij} is zero, then the membership degree $\mu_{\varepsilon_{ij}}$ should be one. The core is also determined experimentally and is a small interval around zero in order to accommodate process noise, disturbances and model-plant mismatches. Note that this method to derive membership functions is common in various fuzzy approaches (Mendonça, Sousa, & Sá da Costa, 2004). The m membership functions $\mu_{\varepsilon_{i1}},\ldots,\mu_{\varepsilon_{im}}$ must be aggregated using a conjunction operator, which assures that a fault is isolated only when all the residuals ε_{ij} are close to zero. The aggregation can be given by

$$\gamma_i = t(\mu_{\varepsilon_{i1}},\ldots,\mu_{\varepsilon_{im}}), \tag{3}$$

where t is a triangular norm, as e.g. the minimum operator. An example of γ_i for two outputs is shown in Fig. 2. Let $\gamma_i(k) \in [0,1]$, $i = 1,\ldots,n$, be called a *fuzzy decision factor*. These values are computed at each time instant k. A vector of fuzzy decision factors can be computed as:

$$\Gamma(k) = [\gamma_1(k)\ \gamma_2(k) \cdots \gamma_n(k)], \tag{4}$$

i.e., one fuzzy decision factor for each fault. A fuzzy decision factor $\gamma_i(k)$ is high only if all the residuals are close to zero.

In order to isolate a fault i, the value of $\gamma_i(k)$ must be higher than a *threshold* T, which must be close to one. Note that the threshold T