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Integrated nonlinear model predictive fault tolerant control and multiple model based fault detection and diagnosis

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ABSTRACT

In this paper, a new fault-tolerant control approach is presented for a class of nonlinear systems, which preserves system stability despite a time delay in fault detection. The faults are assumed to occur in the actuators and are modeled for the general form of affine nonlinear systems. A fault detection and diagnosis (FDD) block is designed based on the multiple model method. The bank of extended Kalman filters (EKF) is used to detect predefined actuator faults and to estimate the unknown parameters of actuator position. The estimated parameters are then used to correct the model of the faulty system and to reconfigure the controller. The reconfigurable controller is designed based on the stabilizing nonlinear model predictive control (NMPC) scheme. On the other hand, in the duration between fault occurrence and fault detection, because of the mismatch between the process and the model, the system states may go off the attraction region. The proposed method is based on designing multiple local controllers for individual predefined faults. Depending on the value of a system variable at the moment of fault detection, one of these controllers will operate. This leads to a stability region of a set of auxiliary equilibrium points (AEPs), which is larger than the attraction region. Moreover, a framework for preserving system stability is presented. Finally, a practical chemical process example is presented to illustrate the effectiveness of this method.

Keywords: Nonlinear model predictive control; Extended Kalman filter; Fault detection and diagnosis; Attraction region; Actuator fault; CSTR

1. Introduction

These days, performance and safety are two essential requirements for industrial systems. Hence, demand for using controllers to simultaneously satisfy these two requirements is growing. In the classical control approach, when a system malfunctions for any reason, its performance may be degraded and the system may even become unstable. So, it is necessary to use fault detection and diagnosis (FDD) and fault tolerant control (FTC) mechanisms in order to improve the reliability and safety. Generally, the FDD methods that can be integrated with FTC approaches are classified into model-based and data-based ones. The model-based methods employ explicit mathematical models of systems. These two approaches can further be divided into quantitative and qualitative schemes (Venkatasubramanian et al., 2003). The selected FDD approach should be matched to the fault tolerant control system (FTCS). In this paper, a fault tolerant predictive control scheme, which is a model-based method, is used as an FTCS. Furthermore, since the mathematical model of the system is available, the model-based FDD approach is chosen.

In order to select the appropriate FDD method, some criteria such as the ability to provide quick detection for real-time implementations, isolability, suitability for FTCS, identifiability for multiple faults, suitability to nonlinear systems and the computational complexity must be taken into consideration. According to the existing methods, parameter estimation and

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multiple model based approaches are more suited to satisfying these criteria (Zhang and Jiang, 2008).

On the other hand, quick fault detection is an important criterion for choosing the right FDD approach. If the FDD is not able to provide timely fault information, an unacceptable delay in fault detection occurs which may lead to system instability. In Mahmoud et al. (2001) and Mahmoud et al. (2003), system stability has been studied in the presence of uncertainties and time-delays in the FDD approach. If the FDD is not able to provide timely information on the fault, system variables may go off the attraction region. So, after reconfiguration, system stability is not guaranteed by the fault-tolerant controller. This problem is one of the major dilemmas in designing fault tolerant controllers (Sun et al., 2009). Using the idea presented in this paper, the size of the attraction region can be enlarged and system stability can be preserved. Because of many important factors of MPC such as the consideration of input and state constraints, uncertainty and time delay in optimization problems, this scheme can be used as a powerful controller in the event of fault occurrence. Some researchers have used the NMPC approach for designing fault tolerant controllers (Benosman and Lum, 2009; Mhaskar et al., 2006a, 2005). A survey of some recent results obtained in the last few years on the fault tolerant control of nonlinear systems has been presented in Benosman (2010).

The present paper integrates the FDD method with the active fault tolerant controller based on the NMPC approach for nonlinear systems with input constraints and concentrates on developing a new reconfiguration mechanism which maintains system performance as much as possible and guarantees stability in the presence of time-delay in FDD. The controller is designed based on the Quasi Infinite MPC (QIMPC) approach (Chen and Allgower, 1998). Although, faults are considered in the actuators, the proposed method can be tailored to fault detection in sensors and systems. The contribution of this paper is to propose a framework for considering the effect of fault detection delay in the design of fault tolerant control systems and the integration of FDD with QIMPC as a fault tolerant approach. The actuator fault for the general form of affine nonlinear system is also modeled.

This paper is organized as follows. In the subsequent section, the FDD method based on extended Kalman filter (EKF) is described. Fault tolerant nonlinear model predictive control is explained in Section 3. In Section 4, the proposed approach to preserve system stability in the presence of time delay in the FDD block is presented. Finally, the simulation results on a chemical reactor are given.

2. Fault detection and diagnosis

In this section, the lock-in-place (LIP) actuator fault is modeled for the general form of nonlinear system (1). Then, the EKF implementation for parameter estimation is expressed. Finally, multiple model-based FDD is introduced.

2.1. *Actuator fault modeling*

The general form of nonlinear system considered in this paper is described by the following equation:

$$\dot{x} = f(x) + G(x)u(t), \quad y = h(x) \tag{1}$$

where $x \in R^n$ is the system state and $u \in R^m$ is the control vector subject to input constraints $u(t) \in U^{nom}$ where U^{nom} is a compact set. In the fault free mode, the ith input constraints are characterized by

$$u_{i\,min}^{\;nom} < u_i < u_{i\,max}^{\;nom} \quad u_i \in U^{nom} \tag{2}$$

Consider the ith fault has occurred and the input constraints are changed as follows:

$$u_{i\,min}^{\;fault} < u_i < u_{i\,max}^{\;fault} \quad u_i \in U^{fault} \tag{3}$$

The LIP fault considered in this paper occurs when the actuator freezes at an unknown value, and does not contribute to the control action. The LIP actuator fault is modeled as

$$u_{i\,min}^{\;fault} = u_{i\,max}^{\;fault} = \bar{u} \tag{4}$$

where $\bar{u}$ is a constant parameter.

In order to implement EKF, the continuous model system must be converted to discrete time. The Euler forward rule or 4th order Runge–Kutta method can be used for discretization. The discrete time system is described by the following difference equation:

$$x(k+1) = f(x(k)) + g(x(k))u(k) + G_v v(t) \tag{5}$$

where $v(t) \in R^{n1}$ is the system noise. This equation can be described in more details by

$$\begin{bmatrix} x_1(k+1) \\ \vdots \\ x_n(k+1) \end{bmatrix} = \begin{bmatrix} f_1(x(k)) \\ \vdots \\ f_n(x(k)) \end{bmatrix} + \begin{bmatrix} g_{11}(x(k)) & \cdots & g_{1p}(x(k)) & \cdots & g_{1m}(x(k)) \\ \vdots & \cdots & \ddots & \cdots & \vdots \\ g_{n1}(x(k)) & \cdots & g_{np}(x(k)) & \cdots & g_{nm}(x(k)) \end{bmatrix} \times \begin{bmatrix} u_1(k) \\ \vdots \\ u_p(k) \\ \vdots \\ u_m(k) \end{bmatrix} + G_v v(t) \tag{6}$$

It is assumed that the LIP actuator fault occurs on pth actuator. So

$$u_p(k) = \overline{u_p}\ \forall\, kT > T^{fault} \tag{7}$$

where $\overline{u_p}$ is a constant unknown parameter to be estimated. T is the sampling time and T^{fault} is the fault instant. In