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Improved infinite horizon LQ tracking control for injection molding process against partial actuator failures

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ABSTRACT

Focusing on injection molding processes with partial actuator failures, a new design of infinite horizon linear quadratic control is introduced. A new state space process model is first derived through input–output process data. Furthermore, an improved infinite horizon linear quadratic control scheme, whereby the process state variables and tracking error can both be regulated separately, is proposed to show enhanced control performance against partial actuator failures and unknown disturbances. Under the circumstances of actuator faults, the closed-loop system is indeed a process with uncertain parameters. Hence, a sufficient condition is proposed to guarantee robust stability is presented using Lyapunov theory. The proposed concepts are illustrated in an injection velocity control case study to show the effectiveness.

1. Introduction

Batch processing technology has achieved a lot of progress in recent years for manufacturing low-volume products with high values. Following the relevant business of batch products, the associated industrial process modeling, optimization and control strategies also developed significantly (Korovessi and Linninger, 2006). However, with the higher demand of product specifications and operation safety, strict process modeling and control issues are required on the batch processes, which may result in control system failures.

In industrial applications, actuators are very important because they provide a link between the controller output and the corresponding physical actions (Villani et al., 2012). However, since physical malfunctions are unavoidable, the ideal commitment of the controller command cannot always be executed, which in fact will lead to actuator faults. For industrial process control systems, such situations eventually lead to deteriorations in terms of process operation and performance. In view of this, fault-tolerant control (FTC) design is a very hot topic and is significantly studied. FTC design aims at letting the controller preserve closed-loop stability and at the same time, provide acceptable process control performance. Recently, there have been a lot of FTC research results. To deal with the six-phase permanent-magnet synchronous motor (PMSM) drive system, an intelligent complementary sliding-mode control was proposed (Lin et al., 2013). Some stability issues of friction-type actuator failures are discussed in (Mosemann et al., 1997). In order to increase the reliability in industrial aerospace actuators, a maximum-likelihood voting algorithm was proposed (Akrad, 2011). A timing compensation approach is implemented in an adaptive actuator failure compensation controller (Wang et al., 2004). Lagerberg and Egardt (2007) presented an estimation algorithm for predicting the backlash phenomenon in the actuators of automotive powertrains. A linear output feedback control approach was shown to stabilize systems with actuator saturation faults (Wu et al., 2007). Mhaskar et al. (2008) propose a multivariable fault-tolerant control for nonlinear systems subject to faults in the control actuator using Lyapunov based controller design strategy, where both cases of all the state can be measured and not all the states can be measured are discussed. In Mhaskar et al. (2006a), the integration of fault-detection, feedback and supervisory control is proposed for nonlinear processes with input constraints subject to control actuator failures, where Lyapunov-based controller and fault-detection filters are adopted to ensure closed-loop system stability. Moreover, a nonlinear observer is also used for cases of failures lack of process state measurements. Under the model predictive control framework, Mhaskar et al. propose two approaches of fault-tolerant control where candidate control configurations are first determined with different manipulated inputs, then performance and robustness considerations are considered in the subsequent control design (Mhaskar et al., 2006b).

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Generally, three kinds of actuator faults, i.e., the partial actuator failure, the actuator outage and the actuator stuck will be encountered in batch processes operation. For the latter two cases, the closed-loop system will not be controllable and it is meaningless to consider further controller designs. Therefore, research on modeling and control methods in dealing with partial actuator faults is a meaningful job for researchers. Though relevant results on FTC design for batch processes are scarce, there have been some results. Scenna (2000) provided some diagnosis and reliability issues of batch processes. A particular 2D Fornasini–Marchsini model based iterative learning controller was proposed by Wang et al. (2006) for batch processes with actuator faults. In Giridhar and El-Farra (2009), unified robust detection, isolation and compensation for actuator faults are proposed. Wang et al. (2012, 2013a) show that by assuming that the process delay is within a pre-described range, the FTC for such processes can be designed through robust iterative learning control (ILC) or guaranteed cost performance control using linear matrix inequality (LMI).

Due to the fact that the actuator fault is not clearly known, the controller is often designed by the assumption that the actuator adopts the controller output accurately, which causes model/plant mismatches to the closed-loop control system (Zhang et al., 2014a). Though there have been some fault diagnosis and control strategies (Abdullah and Zribi, 2013; Huang et al., 2012; Mohammadpour et al., 2014; Freire and Marques Cardoso, 2014), the key issue of enhancing control performance under model/plant mismatch still remains open. Although ILC is widely used for batch processes, it actually relies on the assumption that repetitive nature exists in such processes and therefore performance is greatly confined to this assumption. In practice, many batch processes are nonlinear with non-repetitive dynamics and unknown disturbances, which pose great challenge and difficulty for ILC. Recently, model predictive control (MPC) has also been proposed to improve control performance (Guzman et al., 2013; Nikdel et al., 2014; Zhang et al., 2014b). However, there is still space for further design methods to improve control performance under model/plant mismatch and partial actuator failure (Zhang et al., 2012).

The paper contributes to the design of a new linear quadratic control strategy for batch processes under partial actuator failures, which is an extension of our previous work described in Zhang et al. (2013). On the one hand, the paper proposes a general infinite horizon linear quadratic control (LQ) design on a process with time delay. On the other hand, robustness issues are provided for controller designs to ensure a robust stable control system. In this controller design, the new model structure augments both the time delay and the state variables and enables the controller to bear the LQ structure and simultaneously, unlike traditional infinite horizon LQ (TIHLQ), possesses the advantages of both tuning the process state variables and the output errors. The effectiveness of the proposed LQ is tested on the injection velocity control of an injection molding process with comparison results done through TIHLQ (Kwon and Han, 2005).

The article is organized as follows. Section 2 presents the problem formulation. In Section 3, the traditional LQ strategy is shown. The detailed model derivation and controller design are shown in Section 4. Comparisons of injection velocity control with TIHLQ are fully illustrated in Section 5. Conclusion is in Section 6.

2. Problem formulation

For simplicity, the batch process considered here is assumed to be single-input single-output (SISO), which can be linearized at it operation point as follows:

$$\begin{cases} x(k+1) = \bar{A}x(k) + \bar{B}u(k-d) \\ y(k) = \bar{C}x(k) + w(k) \end{cases} \tag{1}$$

where $0 < k \leq L$ is the current time instant, L is the end time point of batch process operation. $x(k) \in \mathbf{R}^n$, $y(k) \in \mathbf{R}$, and $u(k) \in \mathbf{R}$ are the process state, output and input at time instant k, respectively. d is the dead time and $w(k) \in \mathbf{R}$ is the measurement noise. $\{\bar{A}, \bar{B}, \bar{C}\}$ are the system matrices of appropriate dimensions.

The partial actuator failure is described as follows:

$$u^F(k) = \alpha u(k) \tag{2}$$

where $u(k)$ is the calculated controller output for the actuator, and $u^F(k)$ is the actual control action of the actuator. Here α denotes the impact of the actuator fault and

$$0 < \underline{alpha} \leq \alpha \leq al\bar{p}ha \tag{3}$$

The terms $\underline{\alpha}(\underline{\alpha} \leq 1)$ and $\underline{\alpha}(\bar{\alpha} \geq 1)$ are known as scalars.

Remark 1. Eq. (2) is widely adopted to describe actuator fault systems (Villani et al., 2012; Wang et al., 2006, 2012, 2013b; Yang et al., 2000; Yu, 2005). It is obvious that $\alpha > 0$ corresponds to the partial actuator failure and $\alpha = 0$ is the outage case, hence $\alpha > 0$ is considered in this article. Eq. (3) also shows that α varies within a known range, and we can see that $\underline{\alpha} = \bar{\alpha}$ or $\alpha = 1$ corresponds to the normal case, i.e., there are no partial actuator faults.

Remark 2. Note that some batch processes may have redundancy in their inputs and are therefore controllable even under the complete failure of one or more actuators. Due to the above fact, this article only considers the situation that batch processes do not have such redundancy and actuator faults will pose great impact on the process performance, which should be considered in the control system design.

To summarize, the batch process under partial actuator failures is now described as follows:

$$\begin{cases} x(k+1) = \bar{A}x(k) + \bar{B}\alpha u(k-d) \\ y(k) = \bar{C}x(k) + w(k) \end{cases} \tag{4}$$

The goal of the subsequent control design is to derive a FTC such that the process output tracks the set-point as closely as possible even in case of actuator faults and unknown disturbances.

3. Traditional infinite horizon linear quadratic control

This section shows the idea of traditional infinite horizon linear quadratic control (TIHLQ), which will be used for comparison with the proposed LQ later in the case study. Following the traditional TIHLQ, the controller is based on the nominal process model as follows:

$$\begin{cases} x(k+1) = \bar{A}x(k) + \bar{B}u(k-d) \\ y(k) = \bar{C}x(k) \end{cases} \tag{5}$$

The process model is first treated into the differenced variables as

$$\begin{cases} \Delta x(k+1) = \bar{A}\Delta x(k) + \bar{B}\Delta u(k-d) \\ \Delta y(k) = \bar{C}\Delta x(k) \end{cases} \tag{6}$$

It is noted that the following can be derived:

$$y(k+1) = y(k) + \bar{C}\bar{A}\Delta x(k) + \bar{C}\bar{B}\Delta u(k-d) \tag{7}$$

Combining Eq. (7) with Eq. (6), a new augmented model is derived as

$$x_I(k+1) = A_I x_I(k) + B_I \Delta u(k-d) \tag{8}$$

where

$$x_I(k+1) = \begin{bmatrix} \Delta x(k) \\ y(k) \end{bmatrix}, \quad A_I = \begin{bmatrix} \bar{A} & 0 \\ \bar{C}\bar{A} & 1 \end{bmatrix}, \quad B_I = \begin{bmatrix} \bar{B} \\ \bar{C}\bar{B} \end{bmatrix} \tag{9}$$