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State space model predictive fault-tolerant control for batch processes with partial actuator failure

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ABSTRACT

This paper presents a state space model predictive fault-tolerant control scheme for batch processes with unknown disturbances and partial actuator faults. To develop the model predictive fault-tolerant control, the batch process is first treated into a non-minimal representation using state space transformation. The relevant concepts of the corresponding model predictive fault-tolerant control is thus introduced through state space formulation, where improved closed-loop control performance is achieved even with unknown disturbances and actuator faults, because, unlike traditional model predictive fault-tolerant control, the proposed control method can directly regulate the process output/input changes in the design. For performance comparison, a traditional model predictive fault-tolerant control is also designed. Application to injection velocity control shows that the proposed scheme achieve the design objective well with performance improvement.

1. Introduction

As a preferred method of manufacturing low-volume products with high-value, batch processing technologies have received widespread attention. Though the relevant studies can be dated back to the 1930s, significant progress has only been made for both control technology and application in the last 10 years, driven by the business of manufacturing [1].

Due to the demand of high productivity and strict operation conditions, batch processes are now operated under challenging conditions that possibly lead to system failures. In view of the fact that chemical processes often have a lot of measurement sensors and actuators, if a fault cannot be detected and corrected immediately, process performance will generally deteriorate and even serious safety problems may result causing both the plant and personnel damage. Fault-tolerant control (FTC) is therefore important for maintaining closed-loop control performance even in the presence of faults. Studies on FTC have received considerable attention [2–5]. For batch processes, however, only limited results focusing on fault detection/diagnosis and control are available up to present since batch processes are complex and supporting technologies are not yet mature [6–9]. Moreover, batch processes can also be affected by both the non-repetitive time-invariant and time-varying failures, which make traditional analysis and synthesis of learning-type controller design more difficult.

In practice, actuator faults are often encountered due to frictions, saturations, dead zones, etc., which cause difficulty for the actuator to achieve the desired position. However, the design of controller is always based on the ideal assumption of perfect action of actuator in response to the controller output, which may cause serious deterioration of performance. There have been some research results on fault diagnosis and control of different kinds of process [10–13]. To the best knowledge of the authors, there have only been a few results for batch processes with actuator failures. Some general diagnosis and reliability issues of batch processes are discussed in [7]. For batch processes with actuator failures, Wang et al. [8] propose a 2D iterative learning reliable controller (ILRC) by assuming that the batch process considered can be represented as a 2D Fornasini–Marchsini (2D-FM) model. In [14], a unified robust detection, isolation and compensation for actuator faults are proposed. Wang et al. [15] proposed a robust iterative learning control using state space model by assuming that the process delay is within a pre-described range. Recently, model predictive control (MPC) has also been proposed for process control

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performance improvement [16–18]. Design of MPC technology for controlling batch processes is now transformed into the issue of achieving the desired product quality, together with considering input constraints and faults in the control actuators [19–21].

The above mentioned robust and MPC strategies follow the general idea of designing controllers (whether iterative or not) based on traditional input–output or state space process models, and to guarantee the stable closed-loop fault system, conditions in terms of linear matrix inequality (LMI) or other assumptions are needed. In fact, effectiveness of iterative learning is greatly dependent on the repetitive nature of the process. In practice, many batch processes are slowly time-varying, which causes non-repetitive behavior and thus poses great difficulty for iterative learning methods to achieve fast performance improvement. In addition, the assumptions associated with the subsequent controller design may not be applicable in practice.

Based on the aforementioned facts, a model predictive fault-tolerant control for batch processes is proposed in this paper. The new features of the proposed MPC lie in the following facts. First, unlike traditional process models, the proposed strategy adopts a new state space formulation using process operating data, where information of process state variables and output tracking error are integrated. This new formulation will provide more prediction information for subsequent controller designs. Second, a new MPC is designed using an improved cost index that can include both the tracking error and the state changes, which helps the designer choose relevant weighting factors for improved control performance. The objective of the proposed control is thus to ensure improved output tracking performance under unknown disturbances for both normal operation and in case of admissible faults. An injection velocity control is illustrated to show the feasibility and effectiveness of the proposed method.

Batch processes can be controlled to satisfy the required specifications through different ways. The most common one is linear control strategies since linear theory is simple and effective in a certain range of operation. If process dynamics changes a lot during the whole batch operation, multi-linear process models based control strategies may be the choices to do the job, which first require a number of operation modes tests or experiments, and then the design of subsequent process model identification algorithms and controllers for each operation mode. If a certain trajectory is not a fixed set-point but is time-varying, it can still be tracked through linear control algorithm since this trajectory corresponds to the servo performance of a controller design. The transition from one mode to another is determined by the operating conditions/or the state of the key process variables of the process. Different processes have different variables/conditions measurement. Once such conditions/or the key process variables satisfy the settings, the operation changes to the next operation mode, where the corresponding model and control strategy for this mode is adopted.

If the batch processes' dynamics are highly nonlinear and linear multi-model strategies cannot achieve the satisfactory specifications, nonlinear identification and control strategies may be desirable to satisfy the strict operation specifications. However, this is a more complex job and requires significant efforts.

The paper is organized as follows. Section 2 proposes the problem formulation. In Section 3, the idea of traditional FTC is introduced. The main strategy of the proposed is detailed in Section 4, where the batch process is first transformed into an improved state space formulation and a corresponding MPC is designed using process state weighting and optimization. In Section 5, the effectiveness of the proposed is demonstrated through injection velocity control. Section 6 concludes the paper.

2. Problem formulation

In this paper, it is assumed that the batch process is single-input single-output (SISO). By considering the operation around a set-point, it can be described through linearization as

$$\begin{cases} x(k+1) = Ax(k) + Bu(k-d) \\ y(k) = Cx(k) \end{cases} \tag{1a}$$

$$s.t. \quad 0 \le k \le N \tag{1b}$$

where $x(k) \in \mathbf{R}^n$, $y(k) \in \mathbf{R}$, and $u(k) \in \mathbf{R}$ represent the state, output and input of the process, respectively. d indicates process delay, N is the end time instant. $\{A, B, C\}$ are the system matrices with dimensions of $n \times n$, $n \times 1$ and $1 \times n$.

For the above process, a controller is designed to produce a control signal for the actuator to implement. Let $u^F(k)$ denote the signal from the actuator that has failed. Then, the ideal situation, i.e., there is no fault, is

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

Remark 1. It is noted that batch processes are generally nonlinear in many cases. Batch processes based on nonlinear model is still an open problem. In [22], a linear perturbation model is considered to describe nonlinear batch processes operated around a set-point. Similarly, for nonlinear batch processes, use of the proposed method in this paper is feasible. This can be done by separating the nonlinear modes into several operating points and derive the corresponding linear perturbation models around such operating points. Thus relevant control strategies can be designed for different operating points.

Remark 2. Continuous processes can also be described as Eq. (1a). However, since batch processes are discontinuous and requires intermittent introduction of frequently changing raw materials. Production does not go on all the time, but is performing for a specified period of time. These correspond to the conditions that the set-point is not fixed and the operation duration is finite shown in Eq. (1b).

Due to malfunctions of the actuator, the above ideal case cannot always be achieved, which causes actuator failure. Thus the failure model is adopted as

$$u^F(k) = \alpha u(k) \tag{3}$$

where

$$0 < \alpha \le 1 \tag{4}$$

Remark 3. For actuator failure, mainly three situations are considered: partial failure case, i.e., partial degradation of the actuator, the outage case and the stuck fault, which makes the output of an actuator stay at a constant value. In case of the latter two failures, the control system is no longer controllable. Therefore, a partial failure case model described by Eq. (3) is widely used [23,24].

Remark 4. Let $\alpha > 0$ denote the partial failure case and $\alpha = 0$ the outage case. Then it can be easily seen that $\alpha > 0$ is used in this paper. Meanwhile, α is assumed to vary within a known range that is described by Eq. (4). It is clear that $\alpha = 1$ corresponds to the normal case.

Hence, a batch process with actuator failures can be described by

$$\begin{cases} x(k+1) = Ax(k) + B\alpha u(k-d) \\ y(k) = Cx(k) \end{cases} \tag{5}$$

We are now in a position to find a control law such that the output of the above batch process Eq. (5) tracks the set-point as closely as possible under actuator failures.