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A decoupling approach to integrated fault-tolerant control for linear systems with unmatched non-differentiable faults[☆]

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ABSTRACT

This paper proposes a decoupling approach to the integrated design of fault estimation (FE) and fault-tolerant control (FTC) for linear systems in the presence of unknown bounded actuator faults and perturbations. An adaptive sliding mode augmented state unknown input observer is developed to estimate the system state, actuator faults and perturbations, based on a descriptor augmentation strategy and the *equivalent output injection* concept. Subsequently, an adaptive backstepping FTC controller is designed to compensate the effects of the faults and perturbations acting on the system to ensure robust output tracking. In the proposed observer the effects of the control system perturbations are estimated and the fault effects are compensated to ensure that the FE function is decoupled from the FTC system. This leads to satisfaction of the Separation Principle under the framework of integrated design. When compared with the existing H_∞ optimization single-step integrated FE/FTC design approach, in this paper the FE/FTC decoupling and the perturbation compensation (in the control) together contribute to a new integrated FTC strategy with more design freedom, less complexity and higher robustness. Moreover, the proposed method is shown to be applicable to a wide class of faults, which can be differentiable or non-differentiable, and matched or unmatched. Comparative simulations of the tracking control of a DC motor are provided to demonstrate the performance effectiveness of the proposed approach.

1. Introduction

Fault-tolerant control (FTC) of automatic systems has attracted an increasing research interest aiming to provide admissible robust system performance and improve system safety and reliability, in spite of system perturbations (including system uncertainty and/or external disturbance) and unknown faults (Blanke, Schröder, Kinnaert, Lunze, & Staroswiecki, 2006; Patton, 2015).

For the purpose of fault compensation by FTC design, fault information (magnitude, location, and time occurrence) is required. A direct and effective approach to attain fault information is fault estimation (FE), based on state observers, e.g., the sliding mode observers (SMOs) (Edwards, Spurgeon, & Patton, 2000; Huang, Patton, & Lan, 2016), adaptive observers (Jiang, Staroswiecki, & Cocquempot, 2006), extended state observer (Gao & Ding, 2007), augmented state unknown input observer (ASUIO) (Lan & Patton, 2016), and high order SMO (de Loza, Cieslak, Henry, Zolghadri, & Fridman, 2015). By a suitably designed observer the fault signals can be estimated and then be compensated within the FTC system conveniently (Patton, 2015). Previous studies show that observer-based FE methods can be very effective in FTC as long as appropriate robustness designs are considered.

A complex robustness problem arises when considering observer-based FE and FTC designs. Due to the feedforward action of system control input and output to the observer, the FE performance is affected by the perturbations. The FE feedback into the system through control action, on the other hand, introduces estimation uncertainty to the FTC system. This mutual uncertainty coupling is described as the *bi-directional robustness interactions* between the FE observer and FTC system, which break down the Separation Principle and give rise to a significant problem of integrating FE and FTC designs to achieve required robust FTC performance (Lan & Patton, 2016).

However, most of the existing FTC systems using observer-based FE approach separate the designs of the FE observers and FTC systems (Fig. 1(a)), assuming satisfaction of the Separation Principle (e.g., Gao & Ding, 2007; Jiang et al., 2006; de Loza et al., 2015).

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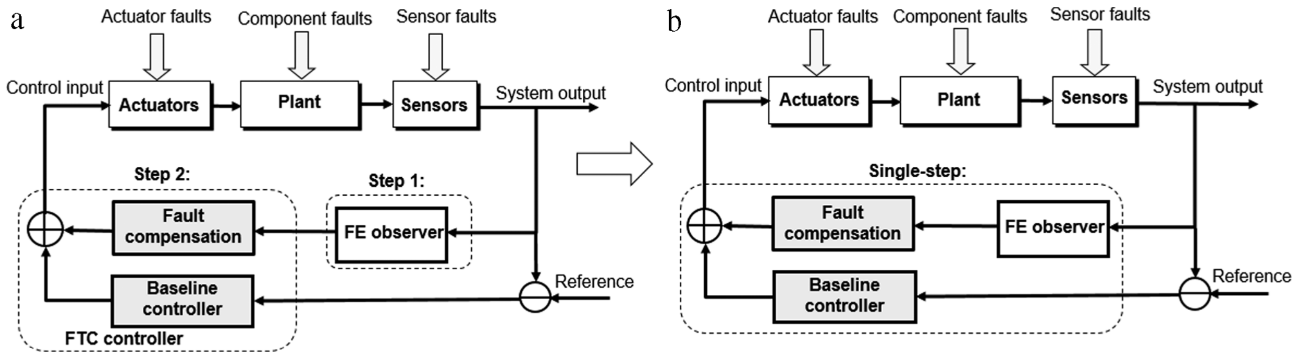

Fig. 1. Observer-based FE and FTC systems: (a) separated method and (b) integrated method (Lan & Patton, 2016).

In Lan and Patton (2016) the concepts of *bi-directional robustness interactions* and integrated FE/FTC design (Fig. 1(b)) are defined. An effective strategy for integrated design for uncertain linear systems subject to actuator/sensor faults has been described, based on the combination of an ASUIO with sliding mode FTC and H_∞ optimization. This integrated approach effectively obtains all the observer and controller gains using a single-step linear matrix inequality (LMI) formulation. However, the approach is limited in the following aspects: (1) The faults considered are assumed to be continuously differentiable (with respect to time) and matched (with respect to the control input), which limits the applicability of the design; (2) Its solution is related to a bilinear matrix inequality (BMI) problem and the linearization to an LMI formulation leads to an approach with low design freedom; (3) The perturbations are suppressed to minimize their effect on the FTC systems, resulting in conservative robust designs.

This paper describes an approach to overcome these limitations in order to achieve a more robust FE/FTC design which can cover a more general class of faults. The system considered here is a linear system with actuator faults and perturbations acting on both the state dynamics and system output. Contributions of this research are summarized as follows.

- *A novel FE observer is proposed to estimate more general faults.* Most FE methods in the literature assume the faults to be continuously differentiable (Gao & Ding, 2007; Jiang et al., 2006; Lan & Patton, 2016; de Loza et al., 2015). There is no such requirement in the SMOs (Edwards et al., 2000; Huang et al., 2016) by using the concept of *equivalent output injection*. However, the SMO (Edwards et al., 2000) has a canonical form in which several coordinate transformations are required. The other SMO (Huang et al., 2016) is designed based on H_∞ optimization. In this paper, a sliding mode ASUIO is proposed to estimate the system state, actuator fault and perturbation, without coordinate transformation and H_∞ optimization. An adaptive gain is introduced to cover the unknown fault bounds.
- *A decoupling FE/FTC approach is developed to offer more design freedom.* By using the descriptor approach in Lan and Patton (2015), the perturbation considered is augmented as a system state and estimated. Therefore, the proposed observer is unaffected by the control system perturbations. Moreover, with an appropriately designed switched component, the effect of the actuator fault on the estimation error dynamics is removed. By combining the above descriptor augmentation and SMO methods, the FE observer is decoupled from the FTC system, which recovers the Separation Principle and allows more freedom for the FE/FTC design. It should be noted that the proposed decoupling approach is different from the separated designs in the literature in that the *bi-directional robustness interactions* are taken in account.
- *Active perturbation cancellation contributes to a more robust FTC system.* As an alternative methodology to H_∞ robust optimization, disturbance-observer-based control has also been used to achieve robust system design (Chen, Yang, Guo, & Li, 2016). In the current work, instead of being suppressed, the perturbations in all the subsystems are compensated actively using adaptive backstepping control (de Loza et al., 2015). A more robust FTC system can then be achieved using this cancellation with an appropriate observer.

The paper is organized as follows. Section 2 formulates the problem. Section 3 describes the adaptive sliding mode ASUIO design and Section 4 presents the adaptive backstepping FTC design. A tutorial example of a DC motor is provided in Section 5. Finally, Section 6 concludes the study.

Notation: The symbol $\mathbb{R}$ is the set of real numbers and $\mathbb{C}$ is the set of complex numbers, $\|\cdot\|$ is the Euclidean norm of a vector and the induced norm of a matrix, I_κ is a $\kappa \times \kappa$ identity matrix, $P_0^\dagger$ is the pseudo-inverse of a matrix P_0 and $\mathrm{He}(P_0) = P_0 + P_0^\top$, $\star$ is the transpose of the element on its symmetric position in a matrix, and $\mathrm{sign}(\omega)$ is the signum function of the variable ω defined by $\mathrm{sign}(\omega) = \omega/\|\omega\|$, and if $\omega = 0$, $\mathrm{sign}(\omega) = 0$.

2. Problem statement

Consider a linear system in the form of

$$\dot{x}(t) = Ax(t) + Bu(t) + Ff(t) + D_1 d(t),$$
$$y(t) = Cx(t) + D_2 d(t), \quad (1)$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$ and $y \in \mathbb{R}^p$ are the state, control input, and measure output vectors, respectively. $f \in \mathbb{R}^l$ is the actuator fault vector. $d \in \mathbb{R}^q$ is the perturbation vector including external disturbance and/or system uncertainty (Chen & Patton, 1999). The constant matrices $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $F \in \mathbb{R}^{n\times l}$, $D_1 \in \mathbb{R}^{n\times q}$, $C \in \mathbb{R}^{p\times n}$, and $D_2 \in \mathbb{R}^{p\times q}$ are known. To simplify the presentation the time index is omitted in the following study. The system (1) is assumed to satisfy the assumptions given below.

Assumption 2.1. The pair (A, C) is observable, the pair (A, B) is controllable, and $\mathrm{rank}(D_2) = q$.

Assumption 2.2. There exists an unknown positive constant f_0 such that $\|f\| \le f_0$. The perturbation d is norm-bounded with a first-order time derivative.

Remark 2.1. It is rational to assume the perturbation d (including system uncertainty and/or external disturbance) to be differentiable. On the one hand, the system uncertainty is a function of the system state variables and it is continuously differentiable. On the other hand, according to the output regulation theory (Isidori, 1995), the external disturbance can be described as a differentiable exogenous system, which represents many disturbances in engineering, e.g., constant and harmonics. Although normally the