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An adaptive actuator failure compensation scheme for a class of nonlinear MIMO systems

X. Yao[a], G. Tao[a,b,*], R. Qi[a], B. Jiang[a]

[a]College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, China
[b]Department of Electrical and Computer Engineering, University of Virginia, USA

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Abstract

This paper develops an adaptive actuator failure compensation scheme for control of a class of nonlinear multi-input–multi-output systems with redundant actuators subject to uncertain failures. The design method is to estimate the failure pattern parameters and the failure signal parameters first, and then use the parameter estimates to construct the adaptive failure compensation controller, the control law calculation is done simultaneously with parameter estimation without explicit failure detection. Closed-loop signal boundedness and asymptotic output tracking, despite the actuator failure uncertainties, are ensured analytically and verified by simulation results from its application to attitude control of a near space vehicle dynamic model.

1. Introduction

For performance-critical control system applications such as aerial vehicles including near space vehicles (NSVs), spacecraft, intelligent cooperating robots, system faults such as actuator failures may cause severe problems such as system performance deterioration and instability. The need of effective fault detection and tolerant control methods has ignited enormous research activities in search for new design methodologies, for accommodating the component failures and maintaining the acceptable system stability and performances, so that abrupt degradation and total system failures can be averted [1–3]. The study of

*Corresponding author at: Department of Electrical and Computer Engineering, University of Virginia, USA.
E-mail address: gt9s@virginia.edu (G. Tao).

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designing and analyzing effective fault-tolerant control (FTC) systems has received considerable attention over the past two decades [5–14].

Primarily, fault detection and isolation (FDI) approaches [11,14] and adaptive control approaches [2] are two typical approaches for fault compensation that have been used in the literature. FDI based designs identify the system fault information and use it to reconfigurate the controller structures. Direct adaptive control based designs are so constructed that they can compensate fault uncertainties by directly adjusting controller parameters adaptively based on system response errors to obtain desired performance, without explicit identification of system faults. Based on such a framework, we have worked on adaptive control of systems with uncertain actuator failures for linear systems and some nonlinear systems [4]. There are still open problems in this direction, and one of them is solved in this paper.

In this paper, we develop a new direct adaptive actuator failure compensation scheme for a class of nonlinear MIMO systems with unknown actuator failures using a direct adaptive control method, by calculating the controller parameters from adaptive estimates of the failure pattern parameters and failure signal parameters. All possible failures can be estimated by a complete parametrization without explicit failure detection, such that the desired performance: closed-loop signal boundedness and asymptotic output tracking, is still achievable despite the uncertainty of the actuator failures.

Our new method of adaptive actuator failure compensation for a class of nonlinear MIMO systems will be applied to an attitude dynamic model of a NSV [16]. NSV attitude dynamics show serious multivariate coupling, high nonlinearity. They inevitably are subject to faults that can be caused by failures of actuators, sensors, or system component damage [17]. Therefore, the reliability and safety of NSVs are of a major concern, and failure compensation mechanisms become desirable for NSV control.

The rest of this paper is organized as follows. In Section 2, the problem of actuator failure compensation for a class of nonlinear MIMO systems is formulated. Then we present the control system model of NSVs, by presenting its attitude dynamics and actuators. In Section 3, we illustrate our procedure on an attitude dynamic model of a NSV, develop a nominal controller structure and parameters with the known actuator failure patterns and parameters. In Section 4, we develop an adaptive actuator failure compensation scheme, design an adaptive law to update the parameters of the proposed actuator compensation controller, analyze the adaptive control system performance, and prove signal boundedness and asymptotic output tracking, followed by the simulation results verifying the desired performance of our adaptive actuator failure compensation scheme.

2. Problem formulation

A class of nonlinear MIMO system. Consider the nonlinear system with m inputs and p outputs in the form of

$$\begin{aligned}\dot{x}_i &= f_i(\overline{x}_i) + g_i(\overline{x}_i)x_{i+1}, \quad 1 \le i \le n-1,\\ \dot{x}_n &= f_n(\overline{x}) + g_n(\overline{x})u(t),\\ y &= x_1,\end{aligned} \tag{1}$$

where $x_i \in R^p (i=1,\ldots,n)$ are the state variables, $\overline{x} = [x_1, \ldots, x_n]^T \in R^{pn}$ and $\overline{x}_i = [x_1, \ldots, x_i]^T$, $y = x_1 \in R^p$ is the output vector, and $u(t) = [u_1(t), u_2(t), \ldots, u_m(t)]^T \in R^m$