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Brief paper

A discrete-time multivariable MRAC scheme applied to a nonlinear aircraft model with structural damage☆

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ABSTRACT

In this paper, a new discrete-time multivariable model reference adaptive control (MRAC) scheme is developed and its application to continuous-time nonlinear systems with structural damage is studied, for which several key technical issues are addressed. The relation of the infinite zero structures of the continuous-time nonlinear system and the linearized discrete-time system is established. Invariance properties of the system infinite zero structure and control gain matrix of the linearized discrete-time system under damage are studied for an aircraft flight control application. Desired system stability and asymptotic output tracking are ensured for the linearized discrete-time system with dynamics and damage uncertainties. A discrete-time linearization-based control design is constructed for control of a high-fidelity continuous-time nonlinear aircraft model with uncertain dynamics and structural damage. Simulation results show the desired system performance and demonstrate the effectiveness of the developed discrete-time adaptive control method for the nonlinear aircraft system model. ∇

1. Introduction

Digital control is widely used in safety-critical systems due to certain advantages over conventional analog control, such as capability of implementing complicated control algorithms and no degradation of performance caused by wear or aging. For fault-tolerant control, a digital control scheme may be constructed either by discretizing a continuous-time control law or by designing a discrete-time control law based on a discretized system model. There is a vast amount of literature on such two discrete-time fault tolerant control methods. For example, as continuous-time fault-tolerant control designs, Chen and Saif (2007), Zhang and Jiang (2008) and Zhang, Parisini, and Polycarpou (2004) presented the reconfigurable control designs based on fault conditions detected by adaptive estimators. In Boskovic, Yu, and Mehra (1998) and Gayaka and Yao (2008), multiple model based switching and tuning schemes were developed. Hitachi and Liu (2010) developed a robust control scheme for aircraft damage compensation. Adaptive control designs without explicitly detecting faults have also been derived to compensate for the actuator failures (Dydek, Annaswamy, & Lavretsky, 2010; Lavretsky, Gadient, & Gregory, 2010; Tancredi, Gu, Phillips, Gururajan, & Napolitano, 2010; Tao, Chen, Tang, & Joshi, 2004) and structural damage (Guo, Tao, & Liu, 2011b; Liu, Tao, & Joshi, 2010; Nguyen, Krishnakumar, Kaneshige, & Nespeca, 2008) respectively. Discrete-time fault-tolerant control schemes have been developed for accommodating uncertain actuator failures in discrete-time systems, see for example Jiang and Chowdhury (2005).

In this paper, we will develop a discrete-time multivariable MRAC scheme for nonlinear systems with damage. A lot of effort has been devoted to developing discrete-time control schemes for nonlinear systems. Yuz and Goodwin (2005) studied discretized nonlinear models of continuous-time nonlinear systems and zero dynamics of the discretized nonlinear models. Grizzle and Kokotović (1988) analyzed feedback linearizability for discretized models of continuous-time nonlinear systems. In Nesic, Teel, and Kokotović (1999), stabilization conditions of discretized nonlinear systems were analyzed. In Barbot, Monaco, Normand-Cyrot, and Pantalos (1992), Monaco and Normand-Cyrot (1987) and Monaco, Normand-Cyrot, and Stornelli (1986), feedback linearization control schemes were investigated for the sampled-data nonlinear systems. However, the feedback linearization control designs may not be suitable for dealing with highly complicated nonlinear dynamics, especially systems with parameter and structural

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uncertainties, such as the nonlinear aircraft flight systems under structural damage conditions. In this paper, we employ a linearization-based discrete-time control design to deal with complexities and uncertainties of the continuous-time nonlinear system with damage.

The infinite zero structure is the key design condition for the multivariable MRAC scheme. In this paper, a new investigation of the infinite zero structure of the linearized discrete-time system is conducted. Based on a thorough study of generic structures of the linearized discrete-time model, we conclude that, when the discretization sampling period is sufficiently small, the infinite zero structure of the linearized discrete-time model is invariant, no matter what the relative degree of the continuous-time nonlinear system is. This property implies that even if the damage changes the relative degree of the continuous-time nonlinear system, the infinite zero structure of the linearized discrete-time model is invariant. Based on such an invariance property, we can develop a discrete-time multivariable MRAC scheme to ensure output tracking of a common reference system chosen from the invariant infinite zero structure.

Then we build a digital control system framework, consisting of the developed linearization-based discrete-time adaptive control law, zero-order holds, and samplers, for the NASA generic transport model (GTM) under possible airframe damage conditions. The GTM is a test aircraft for NASA's AirSTAR flight test facility (Murch, 2008). Many control designs have been successfully implemented in the flight tests or the high-fidelity GTM Simulink simulation model, such as Coffer, Hoagg, and Bernstein (2010), Gregory, Cao, Xargay, Hovakimyan, and Zou (2009), Pandita, Chakraborty, Seiler, and Balas (2009) and Yucelen and Calise (2010). Extensive simulation studies on the high-fidelity GTM Simulink model will be conducted to assess the effectiveness of our developed linearization-based discrete-time control design on the continuous-time nonlinear aircraft system.

New technical contributions of this paper in developing such digital control design techniques include

- obtaining infinite zero structure relation between nonlinear system and its linearized discrete-time model;
- deriving invariance property of infinite zero structure for the linearized discrete-time model under damage;
- developing a discrete-time multivariable MRAC scheme to compensate for uncertainties and to ensure stability and output tracking under damage;
- verifying effectiveness of this linearization-based fault-tolerant control design by extensive simulation studies on the high-fidelity nonlinear GTM Simulink model.

The paper is organized as follows. In Section 2, the linearization-based discrete-time control problem for nonlinear systems under damage is formulated and some key preliminaries are given. Infinite zero structure of the linearized discrete-time model is investigated in Section 3. In Section 4, we develop a new state feedback for output tracking multivariable MRAC scheme to compensate for the damage. In Section 5, design conditions, including the invariance of the infinite zero structure, are verified for a linearized discrete-time aircraft model under damage, and then the developed discrete-time control scheme is applied to the nonlinear GTM to demonstrate desired system performance. Appendix provides proofs of some important properties.

2. Problem statement and preliminaries

Consider a continuous-time nonlinear system

$$\dot{x}(t) = f(x(t)) + g(x(t))u(t)$$
$$y(t) = Cx(t), \qquad (1)$$

where $x(t) \in R^n$ and $u(t) = [u_1(t), \ldots, u_M(t)]^T \in R^M$ are state and control input vector signals, the output vector signal $y(t) \in R^M$ is chosen as a linear combination of the state signals, and f and g_i, $i = 1, 2, \ldots, M$, (with g_i being the ith column of g) are smooth (i.e., C^∞) vector fields defined on R^n. When *structural damage* occurs, the system dynamics f and g in (1) may undergo *uncertain parametric and structural variations*. In this paper, we will design a discrete-time adaptive control scheme to construct a digital control system framework with the addition of samplers and zero-order holds (ZOHs) for control of the nonlinear system (1) to compensate for its possible structural damage.

For the digital control system with ZOHs, the ith control input signal $u_i(t)$ of the nonlinear system (1) is

$$u_i(t) = u_i(kT), \quad kT \le t < (k+1)T, \qquad (2)$$

for $i = 1, 2, \ldots, M$, i.e., within each sampling interval T, the control input signal remains constant. We expand the state signal $x(t)$ in a Taylor series about $x(kT)$ within $t \in [kT, (k+1)T)$, it follows that (Barbot et al., 1992; Kazantzis & Kravaris, 1999; Monaco et al., 1986)

$$x((k+1)T) = x(kT) + \sum_{i=1}^{\infty} \frac{T^i}{i!} \frac{\mathrm{d}^i x}{\mathrm{d}t^i}\bigg|_{t=kT} \triangleq f_d(x(kT), u(kT)). \qquad (3)$$

Since damage causes unknown variations for the nonlinear system (1), the discretized nonlinear model (3) also undergoes uncertain changes. To deal with the uncertainties and complexities of the discrete-time nonlinear model (3), in this paper, we will employ a linearization-based discrete-time adaptive control design.

Linearized discrete-time model. We linearize the discrete-time nonlinear model (3) at an operating point (x_0, u_0), which may not be an equilibrium point due to system uncertainties. Then, a *sequential discrete-time linear model* with an unknown constant dynamics offset f_0 (introduced by the non-equilibrium operating point) can be used to characterize the linearized discrete-time system with damage:

$$\Delta x(k+1) = A\Delta x(k) + B\Delta u(k) + f_0,$$
$$\Delta y(k) = C\Delta x(k), \qquad (4)$$

where perturbation signals are $\Delta x(k) = x(k) - x_0$, $\Delta y(k) = y(k) - Cx_0$, and $\Delta u(k) = u(k) - u_0$, and system matrices and offset are $A = \frac{\partial f_d}{\partial x}\Big|_{(x_0,u_0)}$, $B = \frac{\partial f_d}{\partial u}\Big|_{(x_0,u_0)}$, and $f_0 = f_d(x_0, u_0) - x_0$, which are *unknown piecewise constants*: $(A, B, f_{d0}) = (A_i, B_i, f_{d0_i})$, $i = 1, \ldots, N$, for different *damage* conditions, with N denoting the number of damage scenarios.

Control objective. The objective is to develop a discrete-time adaptive control law $\Delta u(k)$ for the sequential linearized discrete-time model (4) with uncertainties to make all the signals of the closed-loop system bounded and the system output signal $\Delta y(k)$ asymptotically track a reference signal $\Delta y_m(k)$:

$$\Delta y_m(k) = W_m(z)[r](k), \qquad (5)$$

where $W_m(z)$ is stable and $r(k)$ is bounded. The symbol z is used to denote the advance operator: $z[r](k) = r(k+1)$, and $W_m(z)[r](k)$ denotes the time-domain output of the system $W_m(z)$ whose input is $r(k)$.

To proceed the multivariable MRAC design, some preliminaries are given as follows.

Lemma 1 (Tao, 2003). *For any $M \times M$ strictly proper and full rank rational matrix $G(z)$, there exists a lower triangular polynomial matrix*