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Adaptive Fault Detection and Fault-Tolerant Control of NASA Generic Transport Aircraft Model ⋆

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Abstract: In this paper, adaptive fault detection and fault-tolerant control schemes for aircraft flight systems are investigated and evaluated on a high-fidelity aircraft model–the nonlinear NASA generic transport model. State feedback for output tracking and output feedback for output tracking multivariable model reference adaptive control schemes are developed, where plant-model matching conditions are much less restrictive than that of the state feedback for state tracking design, to ensure stability and asymptotic output tracking for the aircraft in the presence of uncertain actuator failures and structural damage. Based on an aircraft system dynamic coupling feature and different actuator failure patterns, adaptive detectors are constructed to detect damage and actuator failures. Our adaptive detection schemes are equipped with feedback fault-tolerant control to ensure signal boundedness requirement. Desired performance of the developed schemes is demonstrated by extensive simulation studies on the nonlinear NASA generic transport model.

Keywords: Actuator failure, adaptive control, aircraft, fault detection, fault-tolerant control, nonlinear systems, structural damage.

1. INTRODUCTION

Malfunctions of aircraft flight systems, such as actuator failures and structural damage, may lead to severe accidents. Reliable fault detection and fault-tolerant control schemes are required to guarantee safety of aircraft systems. Considerable effort has been devoted on designs of actuator failure compensation (Bodson and Groszkiewicz (1997); Boskovic and Mehra (1999)), airframe damage compensation (Bacon and Gregory (2007); Nguyen et al. (2008)), and model-based actuator failure detection (Demetriou and Polycarpou (1998); Wang and Lum (2007)). A challenge of successful fault compensation and detection is the system uncertainty caused by unknown failures and damage, whose onset time instants, patterns and severity are all unforeseen. Adaptive methodologies are capable of autonomously compensate and detect system fault conditions when unforeseen changes in the system dynamics occur. These unique features provide potential to improve flight safety when actuator failures and airframe damage occur. In this paper, we will give a unified framework of designing adaptive fault compensation and fault detection schemes for aircraft systems with actuator failures and damage (Guo, Liu and Tao (2011); Guo, Tao and Liu (2011); Guo and Tao (2011)) and evaluations of proposed designs on a high-fidelity aircraft model–the nonlinear NASA generic transport model (GTM).

Actuator failures and structural damage lead to large unknown parametric and structural variations for aircraft system dynamics. To compensate and detect uncertainties caused by fault conditions, adaptive designs will be applied to the nonlinear aircraft system. Case studies are conducted to conclude that infinite zero structure including interactor matrix and signs of leading principal minors of high frequency gain matrix is invariant under failure and damage conditions, and longitudinal and lateral-directional dynamics are decoupled before damage and coupled after damage. With these two important system model characteristics, adaptive failure and damage compensation and detection schemes can be developed in the presence of large system uncertainties.

For fault-tolerant control of aircraft systems, we apply multivariable model reference adaptive control (MRAC) designs to compensate actuator failures and damage. Since the aircraft model has large parametric uncertainties, it is difficult to use the state feedback for state tracking MRAC design, whose plant-model matching condition is restrictive and hard to be satisfied due to parametric uncertainties. Instead, we use state feedback for output tracking and output feedback for output tracking MRAC designs, whose plant-model matching conditions are less restrictive and satisfiable (Guo, Liu and Tao (2011)) because of the accessible and invariant infinity zero structure. The developed fault-tolerant control schemes are shown to ensure closed-loop system stability and asymptotic output tracking in the presence of uncertain failures and damage.

To enhance system situation awareness, fault detection is needed for aircraft flight systems. Damage detection design is based on the feature that longitudinal and lateral-

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directional dynamics are decoupled before damage and coupled after damage. To capture this cross-coupling characteristic, two adaptive detectors are constructed to estimate decoupled parameters before damage and coupled parameters after damage. Based on residuals between the detectors and the aircraft system, damage detection criteria can be derived to identify the damage. Similar adaptive actuator failure detectors can be constructed based on different failure patterns. Unlike most fault detection schemes operating under an assumption that system signals are bounded before and after faults occur, the developed detection schemes in this paper are equipped with the feedback fault-tolerant MRAC designs that ensure all signals of the closed-loop system are bounded.

The fault-tolerant control and fault detection designs are applied to the nonlinear NASA GTM around a chosen operating point to demonstrate efficacy for improving flight safety in the presence of failure and damage conditions. The GTM is a dynamically scaled test aircraft for the NASA's Airborne Subscale Transport Aircraft Research flight test facility (Murch (2008)) used to test flight research control designs under adverse conditions. In this paper, systematical simulation studies of the developed schemes will be implemented on a high-fidelity Matlab Simulink model of the GTM developed by NASA and new simulation results will be presented. Since the GTM Simulink model can offer a realistic representation of the aircraft under hazardous conditions, simulation results would provide a credible assessment of our designs.

The paper is organized as follows. Section 2 formulates the fault detection and fault-tolerant control problems for aircraft flight systems. In Section 3 and Section 4, multivariable state feedback for output tracking and output feedback for output tracking MRAC schemes are presented to compensate damage and actuator failures, and the developed schemes are evaluated on the nonlinear GTM to assess effectiveness of these linearization-based designs. In Section 5, feedback-based damage detection and actuator failure detection designs are given and nonlinear GTM simulation results are presented to demonstrate effectiveness of the developed fault detection designs. There are also some open issues of fault-tolerant control and fault detection to be addressed in Sections 3, 4, and 5.

2. PROBLEM STATEMENT

The aircraft flight system model can be denoted as

$$\dot{x}(t) = f(x(t), u(t)), \;\; y(t) = Cx(t), \tag{1}$$

where the state signal is $x(t) = [u_b, w_b, q_b, \theta, v_b, r_b, p_b, \phi, \psi]^T$ with u_b, v_b and w_b being the body-axis velocity components of the origin of the body-axis frame whose units are ft/sec, p_b, q_b and r_b being the body-axis components of the angular velocity whose units are rad/sec, ϕ, θ and ψ being the Euler roll, pitch and yaw angles of the aircraft body axes with respect to the reference axes whose units are radian, the output signal $y(t)$ is chosen as a part of the state signal $x(t)$, and the control input signal is $u(t) = [d_e^T, d_t^T, d_r^T, d_a^T]^T$ with d_e, d_r and d_a being deflections of elevator segments, rudder segments and aileron segments whose units are degree, and d_t being engine throttles.

When airframe damage occurs, structure and parameters of $f(x,u)$ are under unknown changes (Bacon and Gregory (2007)). When actuators are failed, they may undergo some uncertain displacements, which can be described as

$$u(t) = (I_m - \sigma)v(t) + \sigma\bar{u}(t), \tag{2}$$

where $v(t)$ is the commanded control input vector signal, $\bar{u}(t)$ is the uncertain failure actuator input, and elements of the failure index $\sigma = \text{diag}\{\sigma_1, \sigma_2 \ldots, \sigma_m\}$ are $\sigma_i = 1$ if the ith actuator fails or $\sigma_i = 0$ otherwise.

Linearized model with a dynamics offset. We will apply linearization-based designs to the nonlinear aircraft flight system (1) for the fault-tolerant control and fault detection problems. Since there are uncertainties for the aircraft system with damage, equilibrium points are not available. Therefore, an arbitrarily chosen operating point (x_0, u_0) is used to obtain a linearized system with a dynamics offset:

$$\Delta\dot{x} = A\Delta x + B\Delta u + f_0, \;\; \Delta y = C\Delta x, \tag{3}$$

where $\Delta x = x - x_0$, $\Delta y = y - Cx_0$ and $\Delta u = u - u_0$ are perturbation signals, and $A = \partial f/\partial x\Big|_{(x_0,u_0)}$, $B = \partial f/\partial u\Big|_{(x_0,u_0)}$ and $f_0 = f(x_0, u_0)$ are unknown piecewise constant parameters and dynamics offset due to different damage conditions.

A benchmark aircraft model–the GTM. Adaptive fault-tolerant control and fault detection designs will be evaluated on a high-fidelity Matlab Simulink model of the NASA generic transport model (GTM), which is a 5.5% dynamically scaled twin-turbine powered test aircraft developed by NASA. After developing adaptive fault-tolerant controller $\Delta u(t)$ for the linearized aircraft model (3), we will apply $u(t) = \Delta u(t) + u_0$ to the nonlinear GTM around a small neighborhood of the chosen operating point (x_0, u_0). Since the GTM Simulink model contains engine dynamics, actuator dynamics, sensor dynamics, etc., provides some structural damage scenarios, such as rudder off, vertical tail off, left outboard flap off, left wing-tip off, left elevator off, and left stabilizer off, and also simulates uncertain actuator failures, nonlinear GTM simulation studies can offer a realistic representation of the aircraft and simulation results would provide a credible assessment of our designs.

Fault-tolerant control and fault detection. In this paper, we will consider the following fault-tolerant control and feedback-based fault detection designs for the GTM:

- state feedback for output tracking multivariable MRAC design for structural damage compensation;
- output feedback for output tracking multivariable MRAC design for structural damage compensation;
- output feedback for output tracking multivariable MRAC design for actuator failure and structural damage compensation;
- state feedback for output tracking multivariable MRAC design for actuator failure and structural damage compensation;
- feedback-based adaptive detection of damage;
- feedback-based adaptive detection of actuator failures and system damage.

3. ADAPTIVE DAMAGE COMPENSATION

For the linearized aircraft model (3) with damage, the parameters (A, B) and the dynamics offset f_0 suffer from