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Closed-loop fault detection for full-envelope flight vehicle with measurement delays

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Abstract A closed-loop fault detection problem is investigated for the full-envelope flight vehicle with measurement delays, where the flight dynamics are modeled as a switched system with delayed feedback signals. The mode-dependent observer-based fault detection filters and state estimation feedback controllers are derived by considering the delays' impact on the control system and fault detection system simultaneously. Then, considering updating lags of the controllers/filters' switching signals which are introduced by the delayed measurement of altitude and Mach number, an asynchronous H_∞ analysis method is proposed and the system model is further augmented to be an asynchronously switched time-delay system. Also, the global stability and desired performance of the augmented system are guaranteed by combining the switched delay-dependent Lyapunov–Krasovskii functional method with the average dwell time method (ADT), and the delay-dependent existing conditions for the controllers and fault detection filters are obtained in the form of the linear matrix inequalities (LMIs). Finally, numerical example based on the hypersonic vehicles and highly maneuverable technology (HiMAT) vehicle is given to demonstrate the merits of the proposed method.

1. Introduction

For the increasing demands of good system performance, feedback information becomes indispensable owing to its key role in the closed-loop control to stabilize the system and acquire desired performances. Feedback information can be obtained through the sensors, but there usually exist a time varying delay between the measured value and its true value in digital systems, owing to the inherent existence of the computation delay, sampling time delay and imperfect communication.[1–3] Especially, for the flight control system, the delayed feedback information will no doubt make the direct application of many excellent traditional control techniques impossible and lead to performance degradation or even system fail.[4,5]

Meanwhile, for modern flight vehicle, especially for hypersonic vehicles and highly maneuverable technology (HiMAT)

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vehicle, there exist dramatic parameter variations and wide velocity range within the full-envelope such that the traditional gain-scheduled method is no longer theoretically feasible.[6] However, the switched system theory meets the necessities mentioned above, because the parameter variations can be naturally described by the switched system evolving upon arbitrary fast switching.[7,8] Therefore, in this paper, a switched system with delayed feedback information is naturally utilized to represent the full-envelope motion equation of the HiMAT vehicle with measurement delays.

Considering that the closed-loop feedback controller in the flight control system is always adopted to achieve the desired system performance, the delayed feedback information will no doubt degrade the control performance. Meanwhile, the fault detection performance will be further influenced, because the fault detection system usually uses the system output as input. Therefore, the common assumption in most existing literature that the controller and fault detection flitter can be designed separately will not always hold. Under that assumption, the fault detection system is designed just for the open-loop control system, which means that there is no control input to the system, or the control input is a predesigned signal related to time only.[9–13] Consequently, the closed-loop fault detection approach is more suitable, because the control system and fault detection system are simultaneously designed to obtain better overall system performance and lower overall complexity.

Although much attention has been paid to the study on the integrated design of control and diagnosis, the closed-loop fault detection problem is still significant and challenging.[14,15] Zhou et al.[16] proposed the closed-loop fault detection problem and show the necessity of the closed-loop fault detection by using the idiographic numerical example to compare the differences between the open-loop method and the closed-loop method. Li and Yang[17] investigated the simultaneous fault detection and control for a class of switched systems, but the controller and the fault detection filter are still separately designed. Feng et al.[18] considered the closed-loop fault detection problem for the networked nonlinear systems with mixed delays and packet losses, but the control system performance had not been considered which means the controller can only make the system stable.

On the other hand, for the flight control system, considering the switching signal is usually dependent on the system state, such as altitude, Mach number and dynamic pressure, the measurement delays will no doubt cause the asynchronous switching problem. Namely, there are time lags between controllers/filters' switching instants and system modes' switching instants.

Initiated by Zhang and his coworkers,[19–21] studies on control or fault detection problem for the asynchronously switched system have received much attention. Lin et al.[22] designed a state feedback stabilization controller and the stability of the switched singular systems with time-varying state delay under asynchronous switching was guaranteed. Considering the existences of time delays and missing measurements simultaneously, Xiang[23] and Lian[24] et al. investigated the H_∞ filtering problem of discrete-time asynchronously switched systems. However, to the best of the authors' knowledge, the closed-loop fault detection for the asynchronously switched time-delay system with feedback control has not been fully investigated, especially for applications to the full-envelope flight vehicle with measurement delays.

Motivated by the above analysis, this paper is concerned with the closed-loop fault detection problem for full-envelope flight vehicle with measurement delays. Firstly, based on Jacobian linearization, a switched linear system model is established to represent the original nonlinear longitudinal model. Then, considering the time-varying measurement delays' influences on the control system and fault detection system simultaneously, mode-dependent observer- based fault detection filters are constructed, and state estimation feedback controllers are proposed such that the closed-loop system output can track a prescribed command signal and detect fault effectively. Furthermore, to overcome the influences of the asynchronous switching problems introduced by measurement delays of altitude and Mach number, an asynchronous H_∞ analysis method is proposed, and an augmented asynchronously switched time-delay system model is also obtained. Meanwhile, the global stability and desired performance cost of the augmented system are guaranteed by combining the switched delay-dependent Lyapunov–Krasovskii functional method with the average dwell time (ADT) method, and delay-dependent existence conditions for controller and fault detection filter are obtained in the form of the linear matrix inequalities (LMIs). Finally, a numerical simulation based on the HiMAT vehicle is given to demonstrate the effectiveness and advantage of the proposed method.

2. Problem formulation

The full-envelope vehicle investigated in this paper is the HiMAT vehicle, an open-loop unstable unmanned aerial vehicle, and is sponsored by NASA and the United States Air Force to incorporate technological advances in many fields, such as a close-coupled canard configuration, advanced transonic aerodynamics and relaxed static stability.[25,26]

To derive the linear system model from nonlinear dynamics within the full envelope,[6–8] 20 uncoupled linear models are borrowed from the NASA reported,[25] where Jacobian linearization have been performed on the specific 20 characteristic operating points. As each linear model can describe the dynamics in the vicinity of the chosen operating point, the 20 models can cover the HiMAT vehicle's nonlinear dynamics within the full envelope,[25] as depicted in Fig. 1.

For simplicity and conciseness, only the longitudinal model has been considered[6–8] to give prominence to the closed-loop

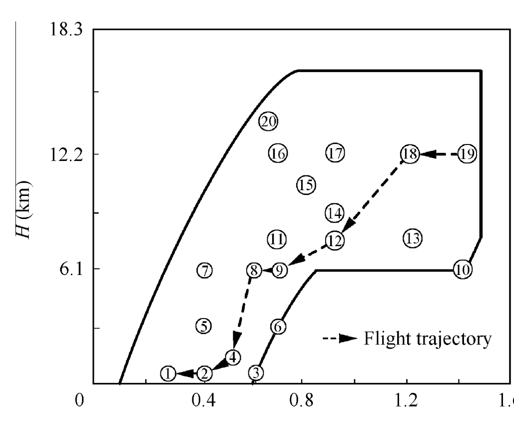

Fig. 1 Flight envelope of HiMAT vehicle.