Fault estimation and fault tolerant control methods for Takagi-Sugeno systems

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Abstract

Nowadays, we are dealing with the increasing complexity of industrial systems, which are often equipped with a large number of sensors and actuators. Industrial processes are usually complex and consequently vulnerable. Process stoppage or poor quality of the final product resulting from system failure can cause serious economic losses, which are often many times higher than the costs of repairing industrial system components. In addition, with the advent of the era of Industry 4.0 and the increase in the degree of automation, robotization and computerization, there is a further increase in the number of system components, sensors and actuators. Such a fact may increase the likelihood of multiple system components faults at the same time. Moreover, the likelihood of multiple faults and resulting economic losses also increases. Therefore, fault estimation is gaining more and more attention both from a practical point of view and is an important aspect in modern fault diagnosis (FD), which can provide knowledge about the presence, location and extent of fault. Such information is necessary to enable active fault-tolerant control (FTC), which can minimize or eliminate losses by applying an appropriate system control strategy.

The main purpose of this research dissertation is to develop a fault-tolerant control strategy based on fault diagnosis with the use in the prediction of the remaining useful life of Takagi-Sugeno system components. The specific objectives were defined as follows:

- Development of methods for estimating simultaneous sensor and actuator faults for Takagi-Sugeno systems.
- Development of fault tolerant control methods tolerating multiple sensor and actuator faults for Takagi-Sugeno systems.
- Development of methods for faults estimation and fault tolerant control with the use of remaining useful life prediction for Takagi-Sugeno systems.
- Implementation and verification of developed methods on selected laboratory systems.
- Conducting a detailed analysis of the functioning of the developed solutions for various fault scenarios.
- Analysis of the obtained results.

The research thesis posed in the doctoral thesis was formulated as follows:

It is possible to develop effective fault-tolerant control using robust observer-based fault estimation and the remaining useful life prediction of Takagi-Sugeno system components, taking into account the simultaneous actuator and sensor faults, as well as disturbances and modeling errors.

Therefore, in the first part of this dissertation, methods of designing the adaptive observer and the observer with the extended state vector for the Takagi-Sugeno system were developed. Moreover, the Takagi-Sugeno system takes into account the possibility of the actuator and sensor faults, as well as possible disturbances in the form of measurement and process uncertainty. Observer robustness was guaranteed using the quadratic boundedness method. The procedure for designing both observers boils down to calculating the obtained linear matrix inequalities and determining the gain matrices. The correctness and accuracy of the both designed observers was verified using a battery system, while Takagi-Sugeno model was developed based on experimental data. In order to verify the effectiveness of the developed method, a fault scenario was proposed in which three types of faults were taken into account, i.e. permanent, slow-growing and temporary, where the sensor and actuator faults at given times occur simultaneously. The obtained results of state and fault estimation were compared between the adaptive observer and the observer with the extended state vector. In addition, the paper also presents the possibility of using the developed estimation method in the task of predicting the remaining battery life in an automatic guided vehicle (AGV).

In the next part of this dissertation, a method of designing fault-tolerant control based on the adaptive observer and the observer with the extended state vector for the Takagi-Sugeno system was developed. In this case, it was also taken into account that the system may be occupied by sensor and actuator faults as well as disturbances in the form of measurement and process uncertainty. The robustness of observers and controllers was guaranteed using the quadratic boundedness method. The procedure for designing a fault tolerant control boils down to the calculation of two linear matrix inequalities and the determination of the gain matrices separately for the observer and the controller. In order to verify the correctness and effectiveness of the proposed method of designing the fault-tolerant control, two objects were used, i.e. the three tank system and a two-rotor aerodynamic system. For both systems, the results were compared between the FTC method based on the adaptive observer and the FTC method using the extended state vector observer. In addition, in order to verify the accuracy and effectiveness of the developed methods, in both cases the fault scenario was taken into account, where three types of faults were used, i.e. permanent, slow-growing and temporary. In addition, the possibility of using the developed methods in remaining useful life prediction of actuators and the time to failure at a given level of fault for a two-rotor aerodynamic system was also presented. The results obtained for both objects were compared for the FTC method based on the adaptive observer and the FTC method using the extended state vector observer. The substantive and experimental results obtained confirmed the high efficiency and correctness of the developed methods of designing the observers used in the fault estimation and the fault-tolerant control methods. Thus, it can be concluded that the adopted thesis has been proven.

Consequently, the most important results contributing to the development of the discipline include:

1. Development of methods for estimating simultaneous sensor and actuator faults for the Takagi-Sugeno system using:

- adaptive observer,
- observer with an extended state vector.

2. Development of control methods tolerating multiple sensor and actuator faults for the Takagi-Sugeno system using:
    - adaptive observer,
    - observer with an extended state vector.
3. The use of the developed observers in the prediction of the remaining useful life of Takagi-Sugeno system components.
4. Validation of the effectiveness and accuracy of the developed methods of faults estimation, multiple fault tolerant control, and prediction of the remaining useful life of Takagi-Sugeno system components for:
    - three tank system,
    - aerodynamic two-rotor system,
    - battery system based on the 2nd order resistor-capacitor circuit model.