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Robust sensor fault detection and isolation of gas turbine engines subjected to time-varying parameter uncertainties ☆

Bahareh Pourbabaee [a], Nader Meskin [b], Khashayar Khorasani [a,*]

[a] Department of Electrical and Computer Engineering, Concordia University, Montreal, Canada
[b] Department of Electrical Engineering, Qatar University, Doha, Qatar

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ABSTRACT

In this paper, a novel robust sensor fault detection and isolation (FDI) strategy using the multiple model-based (MM) approach is proposed that remains robust with respect to both time-varying parameter uncertainties and process and measurement noise in all the channels. The scheme is composed of robust Kalman filters (RKF) that are constructed for multiple piecewise linear (PWL) models that are constructed at various operating points of an uncertain nonlinear system. The parameter uncertainty is modeled by using a time-varying norm bounded admissible structure that affects all the PWL state space matrices. The robust Kalman filter gain matrices are designed by solving two algebraic Riccati equations (AREs) that are expressed as two linear matrix inequality (LMI) feasibility conditions. The proposed multiple RKF-based FDI scheme is simulated for a single spool gas turbine engine to diagnose various sensor faults despite the presence of parameter uncertainties, process and measurement noise. Our comparative studies confirm the superiority of our proposed FDI method when compared to the methods that are available in the literature.

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1. Introduction

Development of an optimal fault detection and isolation (FDI) scheme can lead to and ensure improvements in availability and reliability of safety critical systems such as aero-engines, power networks, chemical processes, wind energy conversion systems, industrial electronic equipments and manufacturing systems. The general procedure of a fault detection and isolation scheme consists of two important steps including: (a) the generation of a residual as the indicator of presence of a fault and (b) the isolation of a faulty element. Fault detection and isolation techniques are broadly divided into two categories, namely model-based and data-driven methods [1–3]. Model-based approaches have been introduced in the survey papers [4–8] and can be grouped into the following approaches, namely (i) observer-based, (ii) parity relations, (iii) optimization-based algorithms, (iv) parametric eigenstructure assignment and (v) parameter estimation and identification techniques.

Observer-based approaches represent an active area within model-based FDI techniques, where the so-called residuals are generated for identifying the fault signatures. The residual signal is sensitive to different factors such as a fault, a

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* Corresponding author.
E-mail address: kash@ece.concordia.ca (K. Khorasani).

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disturbance, modeling error, and uncertainty. Hence, the robustness of any FDI scheme against non-fault related factors the system healthy situation is a substantial feature of any reliable scheme. Two main robust observer methodologies, that is algebraic Riccati equation (ARE) [9] and linear matrix inequality (LMI) approaches have been pursued in the literature.

The uncertainty type can also influence the robust design methodology. The unknown input that is added to the state space equations is a general method for displaying the structured uncertainty due to modeling uncertainties and exogenous disturbances. The unknown input observer is a popular method that was proposed in the literature for decoupling the effects of unknown inputs in [10,11].

The modeling uncertainty can also be represented as polytopic-type structure [12] parameter uncertainty affecting the system matrices and time-varying norm-bounded matrices [13]. Neglected nonlinearities, unmodeled dynamics, and modeling inaccuracies, including physical component faults can also be represented as sources of parameter uncertainties [6]. Through the use of parametric Lyapunov functions, the LMI approach is capable of dealing with these uncertainties by designing less conservative filters [14]. It can also be used to solve multi-objective optimization problems by adjusting the sensitivity of the residual with respect to faults and different uncertainties. One of the advantages of the ARE approach is that the structure and gain of a designed estimator can incorporate and represent effects of parameter uncertainties.

By utilizing the above two approaches, various filtering solutions have been proposed to compensate for the effects of parameter uncertainties, namely as robust H_∞ and H_2 filters [14–16], robust Kalman filters (RKF) and set-valued filters. The robust H_∞ filter is constructed such that the H_∞ norm from the disturbance inputs to the filter error output is minimized. It makes no assumption on the spectral properties of the disturbance signal and is only designed for the worst case signal conditions.

Several results exist in the literature in which an RKF is designed corresponding to either time-varying or steady-state scenarios (associated with finite-horizon or infinite-horizon, respectively). Moreover, upper bounds of estimation error covariances are optimized as obtained in [17]. However, design of RKF strategies when uncertainties are present in the process matrices *has not been investigated* extensively in the literature. In [18] a finite-horizon RKF is developed that achieves a minimized error covariance upper bound for a process subject to parametric uncertainties in all the matrices.

The main issue in design of RKF is to construct an optimal filter that ensures, subject to admissible uncertainties in states and process matrices, a minimum upper bound on the error covariances. It should be noted that this upper bound is not defined *a priori*. In many practical control problems, as in flight path recognition, tracking of a moving target and other stochastic problems, the estimation problem performance requirements can be specified in terms of upper bounds of estimation error variances. Conventional minimum variance filtering methods attempt to minimize the weighted sum of estimation error variances. However, these methods cannot *ensure individual specific desired bounds* corresponding to each state estimation error variance.

The error covariance assignment (ECA) concept was originally proposed in [19] for solving the above problem subject to the desired requirements. Wang [20] extended the ECA scheme to systems having parametric uncertainties by assigning prescribed *a priori* upper bounds on the error variances. Note that these bounds are not guaranteed to be optimal although they satisfy the problem requirements. This solution was also used in [21,22] to tackle various problems and systems.

Mostly in earlier works in the literature, parametric uncertainties are taken into account for a *linear system* with *known* process and measurement noise statistics in *only* the state and measurement matrices. The noise plays an important role in the state error covariance. Consequently, any uncertainty in either its distribution or covariance matrix can affect the accuracy of the estimation process. In this paper we have addressed this issue by assuming that the parametric uncertainties affect *all* the states and measurement matrices as well as process and measurement noise distribution matrices.

Our *first contribution* deals with design of a RKF corresponding to a system with time-varying parametric uncertainties in all the process matrices. It is formally shown that the filtering process is quadratically stable and is guaranteed to satisfy the individually prescribed a *priori* bounds on the state estimation error variances.

Next, our proposed robust infinite-horizon filter is designed for multiple piecewise linear (PWL) models that are obtained at various operating points to cover the entire operating regime of a nonlinear system. Afterwards, a Bayesian approach is applied to generate a general integrated model as well as the combined residuals and covariance matrices that are associated with the robust filters based on the normalized PWL models weights. The integrated model corresponds to the nonlinear system dynamics at any given operating point having a lower approximation error as compared to utilizing a single PWL model. Therefore, our *second contribution* here is interpolation of multiple PWL models as well as the integration of RKF residual vectors and covariance matrices to address the robust estimation problem for the entire operating range of an uncertain nonlinear system.

The above proposed and developed multiple RKFs with their corresponding combined residual vectors and covariance matrices are then applied to solve the sensor FDI problem by using the multiple model (MM) approach for detecting and isolating sensor bias faults corresponding to various severities. Consequently, the *third contribution* of this paper can be stated as design a *robust MM approach* for solving the sensor FDI problem for an entire operating range of a nonlinear system. The advantages and benefits of our approach as compared to the other available robust FDI methods in the literature [23–25] are that one does no longer need to design any static or adaptive thresholds for the fault detection algorithms based upon the *a priori* assumption on the uncertainty level.

The literature available on MM-based FDI approaches [26–28], corresponding to both interacting and non-interacting, represent schemes that are *not* robust with respect to modeling uncertainties.

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