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Data-Driven Fault Isolation in Linear Time-Invariant Systems: A Geometric Approach

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1 abstract

In this work, a data-driven method is proposed for fault isolation in linear time-invariant systems with additive faults. The problem is formulated from a behavioral perspective, utilizing a geometrical approach to distinguish between different faulty modes.

2 Introduction

Fault diagnosis methods provide effective solutions to avoid costly maintenance due to potential malfunctions. The complexity of such systems favors data-driven techniques over classical model-based designs, relying on mathematical models. Recent advancements in data-driven approaches offer an alternative to conventional two-step solutions in which explicit system parameter identification precedes model-based design. In contrast, direct approaches describe the system model in a behavioral setting [1], where a detection filter is developed based on the kernel representation of the healthy system [2]. Fault isolation (FI) problem is a more involved task compared to detection problems, as it reveals the root-cause of faults within the system. While recent data-driven fault detection can be achieved without knowing the system parameters explicitly [3], state-of-the-art FI solutions still remain dependent on this information. In the proposed work, the multi-classification problem is addressed by leveraging the geometry of the underlying problem in the signal space, eliminating the need for the original system parameters unlike the existing works. Compared to the classical solution, it is also easier to scale up for systems with many input-outputs. **Problem Statement:** A fault-free, yet potentially noisy, dataset comprising input-output (I/O) samples of a linear time-invariant system is available during the design stage. We aim to design a diagnosis filter to localize the presence of additive faults, while the underlying system matrices are not known. The system behavior is described as a family of trajectories (u, y) , aiming to classify the regime the system belongs to at any given time k .

3 Framework

To design a diagnosis filter, the system output under operating conditions should be decoupled from the input signal

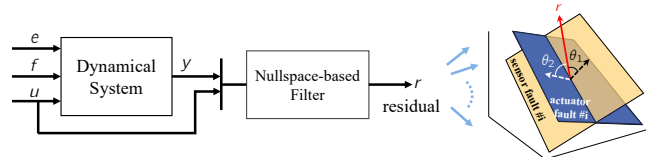


Figure 1: The proposed fault isolation scheme.

and the states, with the remainder referred to as the residual signal. Nullspace-based filters are one of the fundamental techniques for generating the residual signal. In these methods, the left nullspace of the extended observability matrix is exploited to derive a fault detection filter. In this setting, the corresponding subspace must be retrieved from the given data. Additionally, the filter's time window ensures the existence of the left nullspace and defines the ambient space in which the generated trajectories reside. The isolation task processes the information carried in the residual signal to identify the faults' sources. Each element of the multi-dimensional residual signal, generated based on the left nullspace, acts as the output of an individual finite-impulse response filter. The core idea of the proposed framework is to take advantage of this analytic redundancy to determine the faults locations. During the training phase, dictionaries associated with each type of fault are constructed, and the residual signal is projected onto these subspaces. From a geometric perspective, the residual vector should belong to the subspace corresponding to the fault signal. The angle between the residual vector and the projected signal serves as the decision variable in the proposed classifier.

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