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Fault diagnosis using spatial and temporal information with application to railway track circuits

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ABSTRACT

Adequate fault diagnosis requires actual system data to discriminate between healthy behavior and various types of faulty behavior. Especially in large networks, it is often impracticable to monitor a large number of variables for each subsystem. This results in a need for fault diagnosis methods that can work with a limited set of monitoring signals. In this paper, we propose such an approach for fault diagnosis in networks. This approach is knowledge-based and uses the temporal, spatial, and spatio-temporal network dependencies as diagnostic features. These features can be derived from the existing monitoring signals; so no additional sensors are required. Besides that the proposed approach requires only a few monitoring devices, it is, thanks to the use of the spatial dependencies, robust with respect to environmental disturbances. For a railway track circuit example, we show that, without the temporal, spatial, and spatio-temporal features, it is not possible to identify the cause of a detected fault. Including the additional features allows potential causes to be identified. For the track circuit case, based on one signal, we can distinguish between six fault classes.

1. Introduction

In this paper, we propose an approach to fault diagnosis in networks in the presence of environmental disturbances. Because it is often not feasible to monitor a large number of variables for each subsystem in the network, we particularly look into diagnosis strategies that require only a few monitored variables.

With respect to the diagnosis strategy, a choice needs to be made between a model-based, a model-free, or a hybrid approach (see Fig. 1). *Model-based* approaches (Chen and Patton, 2012; Isermann, 2005; Hwang et al., 2010; Nan et al., 2008; Kukal et al., 2009; Fekih et al., 2007) rely on a qualitative or quantitative description of the relations between the monitoring data and system health, while *model-free* approaches (Oukhellou et al., 2010; Cherfi et al., 2012) use historical data and techniques from machine learning or pattern recognition. Finally, *hybrid* approaches (Chen et al., 2008; Sandidzadeh and Dehghani, 2013; Narasimhan et al., 2010) use a combination of the aforementioned strategies. The difficulty with model-free approaches, and to a lesser extent also with hybrid approaches, is that a representative amount of labeled historical data is required, which is in general difficult to obtain (Cherfi et al., 2012). Furthermore, due to preventive maintenance activities, usually only few data samples are available that are characteristic of the natural degradation behavior. For these reasons, we will not further consider model-free and hybrid approaches in this work.

Model-based approaches can be further divided according to the way the model is created (Frank et al., 2000) (see Fig. 1). *Analytical* approaches (Chen and Patton, 2012; Isermann, 2005; Hwang et al., 2010) are based on a quantitative model derived from first principles, *knowledge-based* approaches (Nan et al., 2008; Kukal et al., 2009) use expert knowledge to define a qualitative model of the system, while *data-based* approaches (Fekih et al., 2007) use historical data to learn this model. As we consider applications where data are scarce, and detailed system insight is often difficult to obtain because of system complexity and uncertain environmental disturbances, in this work, a knowledge-based approach is proposed.

The main contribution of this paper is the introduction of a new approach to fault diagnosis in general networks. Key features of this approach are that it relies on the availability of only a limited number of monitoring signals and that it is robust with respect to environmental disturbances. To ensure an adequate diagnosis performance, the following diagnostic features are taken into account:

1. temporal dependencies in the considered subsystem;
2. spatial dependencies within the network;
3. spatio-temporal dependencies within the network.

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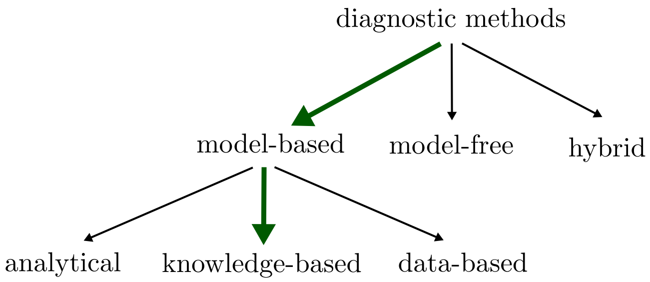

Fig. 1. Classification of the different fault diagnosis methods.

The *temporal dependencies* are valuable for diagnosis because different faults develop in different ways. Knowing the temporal system behavior provides insight into possible fault causes. Similarly, the *spatial dependencies* are useful because they are different for different types of system faults, i.e. some faults only influence one subsystem, whereas other faults influence multiple subsystems. Finally, the *spatio-temporal dependencies* become of interest when objects move through the network. In this case, faulty behavior can be caused by the network itself or by an object moving through the network. Since object faults manifest themselves differently in place and time than network faults, spatio-temporal network dependencies are a suitable feature to discriminate between the two fault categories. The temporal, spatial, and spatio-temporal dependencies can be determined from the available monitoring signals, meaning that they do not require the installation of additional monitoring devices. To the authors' best knowledge, the use of spatial and spatio-temporal dependencies has not been previously proposed for fault diagnosis in networks.

Fig. 2 gives a schematic overview of the proposed diagnosis approach. The proposed method can be used to monitor all kinds of networks where temporal and spatial knowledge is available, e.g., drinking water distribution networks, building infrastructures, and highways. In this work, the applicability of the proposed method is illustrated based on a track circuit diagnosis task.

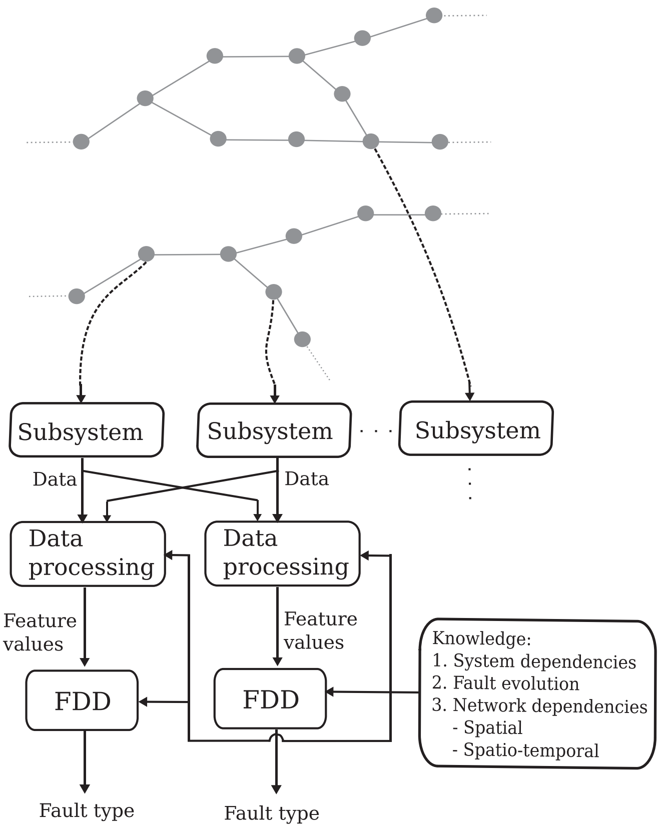

Fig. 2. Overview of the proposed diagnosis approach.

Railway track circuits are used for train detection. Fault diagnosis for railway track circuits has already been dealt with, e.g. by Oukhellou et al. (2010), Cherfi et al. (2012), Chen et al. (2008), Sandidzadeh and Dehghani (2013), Sun and Zhao (2013), and Lin-Hai et al. (2012). A distinction can be made regarding the way the monitoring data are obtained, e.g. using a measurement train (Oukhellou et al., 2010; Cherfi et al., 2012; Sun and Zhao, 2013; Lin-Hai et al., 2012) or using track-side monitoring devices (Chen et al., 2008; Sandidzadeh and Dehghani, 2013). In the current paper, track-side monitoring devices are considered because they continuously monitor the system state and are therefore suitable for the early detection and diagnosis of faults. The main difference compared to the approaches by Chen et al. (2008) and Sandidzadeh and Dehghani (2013) is that in those works multiple monitoring signals are used, while in this paper, for each track circuit, only one measurement signal is available. Although the availability of a wide variety of measured quantities can be beneficial for model-based fault diagnosis (Isermann, 2005), it is not realistic to assume that this will be realized for the whole rail infrastructure, as the related installation and monitoring costs are high. Therefore, we restrict ourselves to one monitoring signal: the current measured at the track circuit receiver.

Note that this paper is an improved and extended version of our conference paper (Verbert et al., 2015). In particular, the current paper adds the following elements: a general framework for fault diagnosis in networks, inclusion of the spatio-temporal dependencies, and a more extensive example.

The paper consists of three parts: 1. a part regarding fault diagnosis in general networks (Section 2), 2. a part covering fault diagnosis in railway track circuit networks (Sections 3 and 4), and 3. a specific track circuit diagnosis example (Section 5).

2. Fault diagnosis in networks

In this section, we propose a knowledge-based approach to fault diagnosis in networks. Fig. 3 gives a schematic overview of the proposed approach. In brief, we collect monitoring signals from the subsystems in the network, correct them for the effect of environmental disturbances (Section 2.3), and extract diagnostic features from the corrected signals. Based on the extracted features (see Section 2.2) and knowledge of the system states (see Section 2.1), we infer the system health. In the remainder, the different steps are worked out in more detail.

2.1. Diagnosis setup

Consider a network consisting of n subsystems[1] that can be graphically represented by a, possibly disconnected, graph (see e.g. the graph in Fig. 2). In this graph, the black dots represent the subsystems and the edges represent connections between the different subsystems. Here, we consider fault diagnosis of an arbitrary subsystem i in the network. We assume that each subsystem i has one healthy mode f_0 and ℓ faulty modes f_1 till f_ℓ. For clarity of presentation and without loss of generality, in the theory part of this paper we consider only single fault scenarios, i.e. the

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[1] For clarity, in the remainder we assume that all subsystems are identical. The proposed method can however be easily extended to networks with different types of subsystems.