Mechanical Systems and Signal Processing 99 (2018) 244–261

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A deviation based assessment methodology for multiple machine health patterns classification and fault detection

Xiaodong Jia *, Chao Jin, Matt Buzza, Yuan Di, David Siegel, Jay Lee

NSF I/UCR Center for Intelligent Maintenance Systems, Department of Mechanical Engineering, University of Cincinnati, PO Box 210072, Cincinnati, OH 45221-0072, USA

ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 11 June 2017
Accepted 17 June 2017

Keywords:
Prognostic and health management
Semiconductor
Bearing
Wind turbine
Principal component analysis
Diffusion map

ABSTRACT

Successful applications of Diffusion Map (DM) in machine failure detection and diagnosis have been reported in several recent studies. DM provides an efficient way to visualize the high-dimensional, complex and nonlinear machine data, and thus suggests more knowledge about the machine under monitoring. In this paper, a DM based methodology named as DM-EVD is proposed for machine degradation assessment, abnormality detection and diagnosis in an online fashion. Several limitations and challenges of using DM for machine health monitoring have been analyzed and addressed. Based on the proposed DM-EVD, a deviation based methodology is then proposed to include more dimension reduction methods. In this work, the incorporation of Laplacian Eigen-map and Principal Component Analysis (PCA) are explored, and the latter algorithm is named as PCA-Dev and is validated in the case study. To show the successful application of the proposed methodology, case studies from diverse fields are presented and investigated in this work. Improved results are reported by benchmarking with other machine learning algorithms.

1. Introduction

Prognostics and Health Management is an emerging engineering discipline with great potential to enhance machine reliability and reduce maintenance cost. In PHM, prognosis is targeting at the incipient/potential machine failures and the prediction of Remaining Useful Life (RUL). Health management is known as a process to develop optimal maintenance strategy for the upcoming failures [1]. Therefore, the major monitoring tasks in an effective PHM system include the monitoring of machine degradation, the detection of machine abnormality and the diagnosis of potential machine failures mode. In lots of applications, these monitoring tasks are implemented in an online fashion, so that the most up-to-date machine health information can be timely extracted and synchronized with the management level to support decision making.

To implement the monitoring tasks mentioned above, many different methods have been proposed. For example, the method of GMM-L2 (Gaussian Mixture Model-L2 distance), SOM-MQE (Self-Organizing Map) and NN (Neural Network)-residue are utilized to assess the wind turbine performance degradation in Ref. [2]. Logistic regression and fuzzy logic are suggested in [3] to evaluate the degradation of elevator door. An Auto-Associative Neural Network (AANN) based method is proposed in [4] to model the anemometer degradation. For machine abnormality detection, PCA-SPE and PCA-T^2 are two of the most commonly used approaches [5]. These two methods can find wide applications in many different fields, like

* Corresponding author.
E-mail address: jiaxg@mail.uc.edu (X. Jia).

http://dx.doi.org/10.1016/j.ymssp.2017.06.015
0888-3270/

semiconductors and chemical process [6]. Other abnormality detection methods also involve the SOM-MQE [7], one-class Support Vector Machine (SVM) [8,9], etc. In regards to methods for fault diagnosis, intelligent classifiers like SVM [10], SOM [11], k-Nearest Neighbor [12] are extensively studied in current literature.

By reviewing these researches, it is found that the monitoring tasks for PHM can be achieved by actually assessing the deviation between monitoring data and baseline data. For physical based approach, the physical models of the machine serves as a reference to detect the deviation of upcoming samples. For data driven approaches, the machine learning algorithms learns the machine normal behavior based on the selected baseline data, the potential machine failures are detected using certain deviation measures, such the L2 distance for GMM-L2 and the MQE value for SOM-MQE. In this study, the main purpose is to propose a novel methodology based on the Dimension Reduction (DR) methods to fulfill the tasks of degradation assessment, abnormality detection and online fault diagnosis. The DR method is desired because it provides an effective way to visualize the high dimensional data, and thus provides more knowledge about why the method may fail in real applications and how to improve the monitoring results. In comparison, the machine learning algorithms, which are known as black-box, provides limited visualization of the data and often requires lots of experience to tune the model properly.

The use of DR method for processing monitoring is not novel. Many DR methods like PCA, kernel PCA, Independent Component Analysis (ICA) have been studied. However, the use of non-linear DR methods, including ISOMAP, Laplacian Eigen-map and Diffusion Map (DM), which is recently found more useful than the traditional DR methods, is still less discussed. These nonlinear DR methods require less prior assumptions and can effectively handle non-linear, high-dimensional and complex dataset. Especially, the performance of diffusion map is found more robust among other peers [13] and a number of successful applications can be found in recent studies. For instance, Li and Zhang [14] suggests improved failure detection rate in semiconductor fabrication process by employing diffusion map. Huang et al. [15] demonstrates the superiority of diffusion map over other peers in clustering different failure modes on the pneumatic pressure regulator test bed. Even though these researches, the application of diffusion map in real application is still less explored and the study of using DM for processing monitoring needs more discussion. Inspired by this, several limitations for using DM for process monitoring are identified in this study and corresponding solutions to address these limitations are proposed accordingly.

The contribution of this paper mainly include following aspects. (1) The limitations of using DM for process monitoring are analyzed and the corresponding solutions are proposed. (2) A DM based methodology for machine health monitoring is proposed, and its applications to the semiconductors and rolling element bearings are presented. Both case studies are based on real world dataset and improved results are reported over other candidate algorithms. (3) A deviation based methodology is proposed based on DM-EVD to include more DR methods and more deviation measures. In this study, the Laplacian Eigen-map and PCA are further fitted into the framework of the deviation based methodology. And the PCA based method is abbreviated as PCA-Dev and validated in wind turbine for performance assessment. (4) Applications of the proposed methodology are presented in diverse fields, including semiconductors, rotating machines and wind turbines.

The rest of the paper is organized as follows. Section 2 details the targeted engineering problems first, and then analyzes the limitation of using diffusion map for multivariate process monitoring. Section 3 outlines a diffusion map based methodology for process monitoring and then generalizes this method to other DR methods. Section 4 presents three industrial applications to demonstrate the effectiveness of the proposed methodology. Conclusion remarks are presented in Section 5.

2. Theoretical background

In this section, the targeted engineering problems are firstly described in details. The potential applications of DR methods are investigated and explored. And also, two typical dimension reduction algorithms, PCA and DM, are reviewed and discussed. Based on these discussions, the current limitations and technical challenges are pointed out and summarized. In the sense of explicitly, these technical challenges are summarized as four questions at the end of this section.

2.1. Statement of engineering problems

The monitoring tasks within the framework of PHM mainly involve the monitoring of machine health or performance degradation, the detection of machine abnormality and the diagnosis of potential machine failure. The monitoring of machine health/performance degradation happens within a relatively longer time window, since the machine degradation is normally a slow process that may span months or years. The monitoring of machine abnormality highlights the timely detection and response to the potential machine failures to avoid any catastrophic consequence. After detecting the presence of potential failures, the diagnosis of possible failure mode is also very important to suggest correct maintenance activities. In most engineering applications, the above mentioned monitoring tasks are expected to process the machine data in an online fashion, so that the most recent machine health information can be synchronized with shop floor management level to support timely decision making. Driven by the needs of timeliness of these PHM tasks, this work mainly explores to implement these tasks in a fashion of process monitoring. In the rest of this sub-section, the above mentioned monitoring tasks will be detailed.