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Joint probability distributions of correlation coefficients in the diagnostics of mobile work machines

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A B S T R A C T

In this paper, we address the problem of diagnostics of mobile hydraulic work machines. A diagnostics method based on the comparison of measurement data of a HIL-simulator and a real mobile work machine using a real time simulation model of an articulated-frame-steered wheel loader is presented. The proposed method includes two phases: training and testing. We use similar set of drive sequences in both phases. In the training phase, the behaviour of an undamaged machine is modelled by probability density functions, which are then used to detect anomalies in the testing phase. In both phases, first, the time series data of multiple variables are segmented into segments of the same length. Correlation coefficients are then calculated for each segment and the distributions of the correlation coefficients are estimated by computing probability density functions using histograms. Finally, the joint probabilities that the correlations in the data segments of the time series data are observed are calculated using the already computed histograms. In faulty systems, occurrence of correlation coefficients changes, which can be used to detect anomalies by comparing the training and testing joint probabilities. The diagnostics is finally based on the combination of static threshold and threshold based on mean value of joint probabilities. This enables the detection of both the single segments with low joint probability value, which indicates high probability of an anomaly, and also the changing trends in the joint probabilities. Simulated faults in the main hydraulic components of the hydrostatic transmission and the working hydraulics of mobile work machine were used as anomalies to study the changes in the joint probability values and to verify the diagnostics method. Finally, the efficacy and the sensitivity of the proposed diagnostics method is presented with promising results regarding detection of faults situations of mobile work machine.

1. Introduction

Service operations have today a major role in the business of machine manufacturing companies. Many manufacturers of mobile work machines, e.g. excavators, cranes and rock crushers, are currently pursuing increased volume and improved performance from their service departments. Typically, these modern machines contain a lot of automation and control systems which provide data about the operation of the machine through communication buses but may also make the localization of failures time-consuming and the detection of evolving failures difficult. So the main challenge is related to analysing [1–4] the data masses and forming of accurate models for component failures [5,6]. Even though the characteristics and condition of an individual component can be accurately defined and modelled based on laboratory tests, reliable diagnostics is far more challenging in field conditions. There, an individual component is one of hundreds of components in a whole machine, which operates in a variable environment and under variable loads. The relatively low cost of mobile work machines also restricts the use of sensors and measurement systems for diagnostic purposes.

The use of simulation models in the development of highly automated machines is becoming a necessity [6,7]. Models are typically created during the early development phase of a machine. Furthermore, hardware-in-the-loop (HIL) simulator systems [5,7–9] enable the connecting of simulation models with parts of the real system. However, these simulation models are not effectively utilized in the later phases of product lifecycle. It is the purpose of this paper to use these simulation models for diagnostics [5,10,11] of mobile work machines. We will use simulation models as a sample of an undamaged machine. Based on this, we build statistical

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model using certain drive sequences of this undamaged machine and a real undamaged machine.

Diagnostics and fault detection of machine systems have been studied widely and significant amount of literature exist of it. Segmentation and feature extraction are two major components of time series analysis employed in diagnostics. Segmentation [12,13] is a method which allows the dividing of time series data into smaller groups of data sets which describe the patterns of the measured variables. Feature extraction involves extracting relevant and discriminating information, and in so doing, reducing data dimensionality. Common feature extraction methods include for example descriptive statistics [14], wavelet transform [14–17], principal component analysis [14,17,18] etc. The extracted features of segmented data are then used to derive the state of the system (e.g. normal, faulty). The features are often classified using different classification methods such as Self-Organizing Maps (SOMs) [14,19], k-means [12,20-22], histograms [23] and Bayesian network classifiers [24].

Diagnostic techniques can be generally classified into two approaches, depending on whether the diagnostics assessment is based on deterministic or on stochastic information (e.g. historical, statistical parameters) [25]. Kim [25] has studied machine prognostics based on health state probability estimation. The methodology assumes that machine degradation consist of a series of degraded states which effectively represent the stochastic process of machine failure. Dongliang [26] has studied estimation of stochastic degradation models. Dongliang [26] states that probabilistic models are mostly employed because of the random nature of the degradation process.

This paper proposes a method for using HIL-simulators for the diagnostics of mobile work machines where the responses of the simulation model and a real machine are analysed and compared from a stochastic point of view based on probabilities. The diagnostics procedure goes as follows: maintenance personnel measure data from the mobile work machine in the working area on the field and send it to the service centre. The measured data includes control signals and corresponding output signals, i.e. responses of the system. In the service centre the measured control signals are used as input in the HIL-simulator and output results are analysed and compared to real measured signals of the mobile work machine.

Comparing the responses of a real work machine and a corresponding simulator system can reveal deteriorated conditions and evolving failures. We propose a statistical method called a joint probability distribution for this purpose. It is based on estimating probability density functions (PDF) of correlation coefficients for segmented multivariate time series data using histograms. These histograms are then used to derive the joint probability values and furthermore the distributions of these values. Comparison of the joint probability values of multiple variables of whole drive sequence or individual segment enables us to detect effectively different anomalies. On the basis of this information further actions can be targeted on essential subsystems and specific work movements.

The main goal is not to try to allocate reasons for possible differences to a specific part of a component or even to a component. The output from the analysis is to verify whether all machine functions correspond to the requirements and to reveal response anomalies and other characteristics in machine operation.

In the next section, the principle of using HIL-simulators in the diagnostics of mobile work machinery is presented. After that, the test platform, a HIL simulation model of a small prototype wheel loader is introduced. Then statistical analysis methods used to compare different simulation models (machines) are described followed by the experiments and the analysis results. Finally, the last section summarizes our conclusions.

2. Mobile work machine and corresponding HIL simulator system

The studied mobile work machine, called GIM-machine [27], is a modified version of the Avant multipurpose wheel loader [28]. It has been designed to serve as a platform for different types of research to be conducted. The frame of the machine is original, but the control system, electronics and hydraulics have been changed for research purposes. The control system of the GIM-machine includes: navigation, mapping, dynamic path planning and obstacle avoidance functions and it can be driven autonomously by a remote operator. Autonomous manipulation functions, such as pallet picking, snow plough, and construction material handling are also made possible. The studied mobile work machine is shown in Fig. 1.

Fig. 2 shows a simplified hydraulic circuit of the hydrostatic transmission (HST) and the working hydraulics of this research platform. The hydrostatic transmission is implemented with an electronically actuated variable displacement pump and fixed displacement motors. The machine has articulated-frame-steering (AFS) with a hydraulic cylinder. The stroke of the steering cylinder is controlled by means of an electronically actuated proportional valve as well as other cylinders (boom, telescope and bucket)

Fig. 1. Mobile work machine.

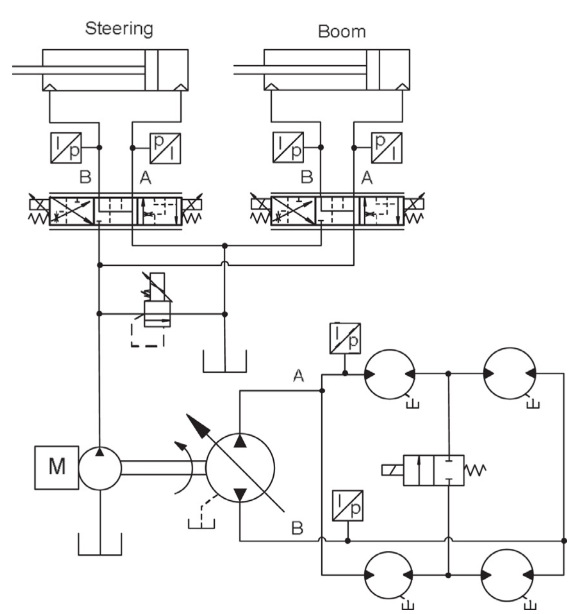

Fig. 2. Simplified hydraulic circuit.

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