EXPERIENCE WITH KNOWLEDGE-BASED SYSTEMS FOR MAINTENANCE DIAGNOSIS

Dieter Wach
Institute for Safety Technology (ISTec), Garching near Munich, Germany

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Contents

Summary

Early fault detection and condition monitoring systems based on deep knowledge about normal and fault-affected signatures (patterns) measured at relevant components have been developed in the last three decades in nuclear industry and related institutes. Similar concepts are published from other industries. By means of on-line data analysis and links to comprehensive signature data banks and proven failure models a good basis is provided for assessment of the actual status of the monitored objects.

Two benefits are obvious: on one hand improved operational safety and useful information to the operators of a plant, of a technical system, or of a mobile craft during operation (on-line or on-board diagnosis) and on the other hand increased efficiency of maintenance by better planning, guided inspections, and improvement of repair and maintenance strategies (off-line or off-board diagnosis). Automation of the fault diagnosis process has been intended in order to reduce human loads for multi-feature monitoring and assessment by application of “intelligent” computer-based means such as logic arrays, pattern recognition techniques, expert systems, neural nets, and knowledge-based systems.

The chapter gives a survey of such advanced diagnosis systems in different industries and the corresponding experience so far. Several examples are presented, most of them from developments for nuclear power plants. Examples from other industries (aircraft, car/truck, railways) are briefly described showing the variety of maintenance/diagnosis tasks but also similarity of the basic concepts. Based on the experiences from practical application future needs and expected trends are discussed.

1. Introduction

During operation technical systems are exposed to continuous loads resulting from static or dynamic strains caused either by the processes themselves (which are conducted by the systems) or by severe environmental conditions. These loads may lead to malfunctions or wear of particular components or parts, to fatigue of certain material, and – by the way –to the loss of partial systems or to break-down of the total system.

An unscheduled loss of a system, however, may cause considerable costs and by the loss of the intended process as well as by the component defect itself or resulting consequent damages. Therefore, it is good practice to monitor not only the process with respect to its key load parameters, but also to perform inspections and repetitive tests at system components in certain intervals during shut-down of the plant (system).

In order to reduce the necessary time and frequency of such tests great efforts have been spent in the past to collect comprehensive knowledge of the actual status (condition) of system components by application of improved on-line monitoring and more sensitive measuring techniques, more global surveillance systems, and knowledge-based condition assessment methods.

A change in the maintenance strategy could be performed towards condition-oriented inspection intervals and so to more cost-effective maintenance. A great impact to these development projects has been caused by the technology progress in the following three knowledge areas:

- Further development of measuring techniques (feature extraction techniques, multi-sensor-based condition monitoring, long-term trending, signature and fault effect analysis, knowledge acquisition techniques)
- Use of tools and methods provided by computer science (classification methods, model- based methods, expert systems, rule-based reasoning, statistical analysis, nearest neighboring methods, inference engines, neural nets, fuzzy technology)
- Performance of new generation computer technology (complex algorithm calculation, flexible data banks, computational speed, Fast Fourier Transform, correlation analysis, data transfer to central diagnosis facilities, enormous cost reduction).

The present chapter is concerned with examples of maintenance supporting systems mainly developed for nuclear power plants. A survey is given with examples whose diagnosis aims having been intended since early times and whose operational experiences could be gained so far. In a second part also a brief review of developments in other industries is given, e.g. in industries of automotive (mobile) systems such as aircrafts, cars and trucks, railways.

In the bibliography further publications and major conferences are referenced from which additional information about the progress of advanced maintenance diagnosis (or the present state-of-the-art in this field respectively) can be derived. At first briefly the history of development steps and the basic characteristics of applied methods are described.

2. Development Steps in Methodology

2.1. History of Early Fault Detection

In the 1970s and 1980s a great euphoria existed to introduce expert systems in nearly all fields of human science and advanced technical solutions. Substantial support in evaluation of complex situations or technical systems should be provided by automated reasoning (inference engine) from a broad knowledge-base even under uncertainties and partial in-transparencies of observed phenomena.

The euphoric expectations were distinctly damped when it became clear that in the real technical world the systematic collection and acquisition of knowledge was not sufficient and had to be intensified much more including context knowledge and uncertainties. In addition, when going to practice it was recognized that the performance and stability of the computers at that time were not sufficient for these kinds of tasks.

To cope with the problems at least in nuclear power plants first another concept was developed. It is characterized by a comprehensive systematic deep knowledge acquisition parallel to the development of new sensitive global multi-channel measurement techniques. For these methods it became popular to use the notation “Early Fault Detection” (EFD).

The main task and first step of EFD is to identify suitable signatures (functions) and features (characteristic values) in accessible measuring signals which can be used for global monitoring of the system and as early warning indicators which utilize the knowledge of fault-generated changes in a set of features (feature vector). An essential difference from conventional monitoring techniques is that not an alarm level representing the maximal allowed load to the system is triggering an assessment, but the magnitude of the feature as soon as it deviates significantly from the reference state (alert level).

It was in the 1960s when in several nuclear power plants (NPP) damages occurred at mechanical structures of primary circuit components (in particular vessel internals) which caused long shut-down times and considerable costs to repair these (radiating) components. Since safety of NPPs always had highest priority, since the components are not accessible during operation, and since additional sensors within the pressure retaining boundary (300 bar, high radiation) were not feasible due to safety (and cost) reasons, research projects were started aimed at measuring methods which are able to monitor on-line the vibrational status of reactor vessel internals and primary circuit components and to detect faults at an early (incipient) stage.

Investigations to identify reliable information on the structural behavior in the dynamic part of the measuring signals of the already existing operational instrumentation (noise of the DC-signals) were very successful. The noise signals of in-core and ex-vessel neutron sensors as well as the fluctuations of coolant pressure signals were found to provide sensitive information about the structure vibrations and other anomalies (in process, instrumentation, or system). Together with additional sensors (vibration and acoustic gauges) adapted at the outer surface of the primary circuit a multi-sensor-system could be developed which allows a global on-line monitoring for early fault detection in NPP primary circuits.

The focus of the research work at that time was in the model development of physical processes and mechanical structures in order to understand the various signal sources and the contributions of structure vibrations of the coupled multi-mass-system. Signatures and features were identified and investigated with respect to operational influences and long-term behavior. Using the physical and structural models, faults and disturbing influences were simulated and sensitivity studies with model parameters were performed to establish a broad knowledge base for fault diagnosis.

2.2. Needs for Knowledge-based Methods

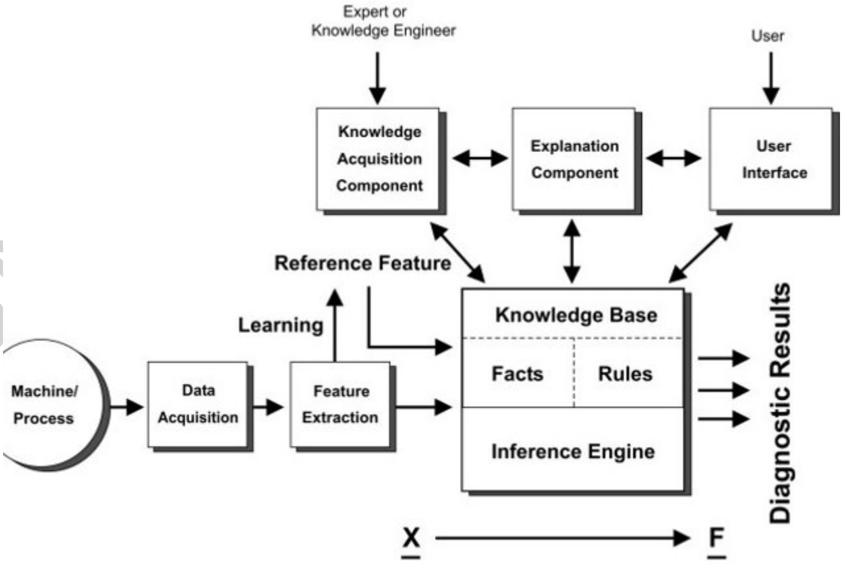

Figure 1. Basic scheme of a diagnosis system

From the practical point of view (needs of plant operators, cost reduction) it was clear that the assessment of the symptoms (corresponding with the feature set changes) and the provision of diagnosis results should be done automatically to the most possible extent. Fig. 1 shows the basic scheme of a diagnosis system: From data measured at a machine, component or process features are extracted, compared with reference features and interpreted by use of a broad knowledge base with automatic reasoning to get the diagnosis results. If the knowledge-base comprises all the expert knowledge, explanation and heuristic knowledge the inference engine can provide correct diagnoses.

In the beginning the collection of broad operational knowledge was done “manually” using multi-channel magnetic tape recorders and off-line-analyses. The assessment of feature changes was performed fully by human experts. In a second phase on site computerized data acquisition, signal analysis, feature trending, and monitoring as well as storage of relevant data were established. From that time on evaluation and assessment have been done partly on site, but in majority (even today) at a diagnosis centre by human experts (after signature and data transfer). Here all incoming signatures from many plants are not only assessed (i.e. diagnosis as an expert service) but are also used to built up a comprehensive data bank and knowledge base together with the fault and simulation models.

In parallel, R&D projects were performed to integrate intelligent tools for automated feature monitoring and fault or status diagnosis. Solutions for well-defined (partial) tasks could be developed and applied in practice. Therefore, it was a favorable circumstance that early fault detection and the intensions to automate diagnoses of system conditions could be enforced and developed in parallel. The development and implementation of automated diagnostic capabilities could be realized stepwise. Concerning the overall (global) monitoring, a combination of knowledge-based methods with integration of human experts has been found to be the most effective way. The main development steps for early fault detection shall be demonstrated using examples from nuclear developments.

3. Basic Characteristics of Early Fault Detection Methods

3.1. Reference Signatures, Feature Extraction and Long-term Trending

Early fault detection is based on two principles: It starts from a well-known “healthy” state of the system represented by signatures (which have to be determined during “base-line” reference measurements and analyses) and then is realized by the sensitive recognition and trending of changes of features. Analysis of random (stochastic) signals can be performed either in time domain or in frequency domain. In both domains signatures and features can be defined and calculated. Changes of “extracted” features have to be related to faults or malfunctions.

Time domain should be preferred when pulse-type excitation influences the component (e.g. metal-to metal impacts of loose parts, defect balls in bearings, relaxation of constrains). Features in time domain may be: statistical moments like variance, skewness, kurtosis; related values like: crest factor, burst slope/gravity ratio, short-term root-mean-square (RMS)-values; signatures: multi-channel burst pattern; histograms (maximal amplitudes, amplitude distribution, delay time distribution). Features or signatures, however, can also be: profiles of transient processes (e.g. pressure increase during opening of valves, during start-up of pumps), on-/off-switching times, delay times (e.g. path-dependent delays of acoustic wave fronts).

Frequency domain analysis is ideal for stationary random signals like structure vibrations, since in spectra (Power Spectral Densities) the structure parameters of vibrating coupled components are well reflected in individual peaks; the frequencies and shapes of the peaks can be related to corresponding components (natural frequencies, damping factors, masses). Simulation models verified during the base-line analysis are used for feature identification and parameter variation analysis. The correlation analysis turned out to be very useful for identification of common signal sources in the signals of spatially distributed and/or physically diverse sensors. Again the frequency domain with cross power spectral densities, coherence and phase functions, transfer functions, etc. is recommended. Fast Fourier Transform, frequency solution and averaging time windows can be used to optimize feature selection (extraction).

So-called waterfall representations of spectra (superimposed spectra at subsequent times) are useful to detect peak-shifts just by eye; of course the trending of peaks can be done more objective graphically by strip charts; in addition first and second order alert levels (or tolerance bands) can be marked. Using these trends and the broad model knowledge the conclusions to the original fault causes can be drawn, i.e. by correct diagnosis of the signature or feature changes information for immediate actions during operation or later for maintenance measures can be provided. The knowledge how to assign the feature or signature to different operational domains (e.g. different power level, flow conditions, excitation) is certainly important and has to be identified during base-line measurements.

3.2. Model-based vs. Signal (Feature)-based Surveillance

In cases in which the process to be monitored can be sufficiently described by a simulation model (a frequently used procedure for rather simple processes) the difference between the actually measured and calculated values (driving forces and system output signals) can be used for fault or pending failure surveillance. The resulting residuals are monitored within tolerance limits which have to be estimated and adjusted by experience. The model-based surveillance (described often in conference papers and research reports) has the great advantage that changed operational domains can be considered via the model parameters. In practice, however, they are not so often used due to limitations such as: idealization of the models, inexact knowledge of parameters and driving forces, or limited ranges of validity of the models.

For complex technical processes or systems (such as the coupled multi-mass primary system in a Pressurized Water Reactor consisting of reactor vessel internals, loops, pumps, and steam generators) a consistent on-line simulating model is not possible. Therefore, the surveillance is based on feature monitoring within tolerance bands. Dependencies between features or their changes respectively are used for diagnosis. They can be considered by logic networks, rule-based assessment (IF-THEN rules) or other inference engines. In literature often a generic difference between “model-based” and “signal-based” methods is stressed. In reality of course also the signal-based methods fully rely on the knowledge about the model behavior of the features; the only difference is that the model investigations have been done off-line in advance, since tolerance bands and mutual relations between features can not be calculated on-line in real-time. The great advantage of feature-based surveillance is in the rather easy feasibility also of large feature vectors, the monitoring of individual and mutual behavior of feature components, and the possibility to consider heuristic knowledge.

Aim of the further development was (and still is) to transfer the assessment of the condition and the derivation of diagnoses to a far-reaching degree to “intelligent” systems. The main difficulties result from the fact, that often the knowledge is not complete or not exact (in-transparency of complex systems) and so conclusions have to be drawn from unreliable (partial) assessment results. The diagnoses may be split up into several hypotheses. A quantitative statement of the probability of the final diagnosis would be helpful.

For automated classification of feature vectors the following methods have been used depending on availability of data, facts, material, and knowledge

- statistical classification (using representative cases, pattern recognition, nearest neighboring techniques)
- model-based classification (using functional models of base-line signatures, fault models of the system, or structural models of the system)
- safe classification (i.e. complete assertion of symptoms to faults in case of complete event trees or decision tables)
- heuristic classification (in case of expert knowledge or observations)
- neural classification (by neural nets without and with implementation of fuzzy techniques).

Applied classification methods and used knowledge bases will be discussed together with the examples in section 4 and 5. In practice it became evident that between aims and feasible automation even today a discrepancy still exists so that many R&D activities are aimed to improvements in this field.

3.3. Signature Data Banks for Centralized Diagnosis Services

Diagnoses of changed conditions of the monitored object have to be derived from the observations of the feature vector, i.e. of the individual components and the mutual relationships between these feature components. Comprehensive knowledge of the model is needed to conclude to the origins of the changes and so to the faults or malfunctions. In addition there is a lot of heuristic knowledge which has to be considered for diagnosis. It is clear that a human expert with his cognitive (context considering) capabilities and access to heuristic knowledge would be the best to give diagnoses. However, using such systems in many plants the permanent availability of an expert is not feasible - neither from the costs and efforts nor the quick response point of view. Therefore, signal acquisition, processing, calculation of signatures and features (or feature vectors), monitoring of tolerance bands, and storage of relevant data should be automated in any case.

The experiences from different application domains (mobile vehicles as well as plants) show that independent of the chosen classification or monitoring method, the systematic collection of operation knowledge, of data from diagnosed events, of long-term influences, of operation status dependability, etc., is extremely important. Therefore, in all application domains central signature data banks have been established to which the online measured data or reduced pre-analyzed data are transferred by means of telephone lines, internet, wireless, or data carriers (streamer tape, floppy disc, CDs). In these centers detailed analyses and comparison with reference and fault signatures are performed (more and more with computer-aided comfort). Implementing all the incoming events and remarkable signatures a continuously growing knowledge base can be established. In this way a (rather) small team of experts is able to give effective support in diagnosis to operators and maintenance personnel.

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Biographical Sketch

Dieter H. WACH, born 1944 (diploma in electrical/electronic engineering at Technical University Munich 1969, Dr.-Ing. (Ph.D.) in nuclear engineering at TU Munich 1976) started research in correlation analysis, surveillance, and diagnostics for nuclear power plants at a nuclear safety laboratory of TU Munich in 1969, continued this work from 1977 on as head of the Instrumentation & Control Department in GRS Garching (Gesellschaft für Anlagen- und Reaktorsicherheit - a research and consulting organization of Governmental Ministries) and later in ISTec Garching (Institute for Safety Technology - a subsidiary of GRS).

Systems based on the developed online monitoring and early failure diagnosis methods have been installed in most of the German nuclear power plants and are applied in many other countries. He is member of various national and international committees and working groups, was frequently session chairman in international conferences and expert meetings, and member of international organizing committees of conferences (such as SMORN, IFAC/Safeprocess, IMEKO/Technical Diagnostics, IMORN, SFM/SFA).

In 1986 he has been offered a chair for Measurement Technology at Technical University Berlin. In favor of a planned new institute for applied research and services in Munich/Garching he rejected this honorable call. His current interests are in safety assessment and licensing issues of digital software-based I&C

safety systems as well as in further development of surveillance and diagnostics for condition monitoring and maintenance support. Recently he became member of the executive management of ISTec, responsible for research and development promotion.