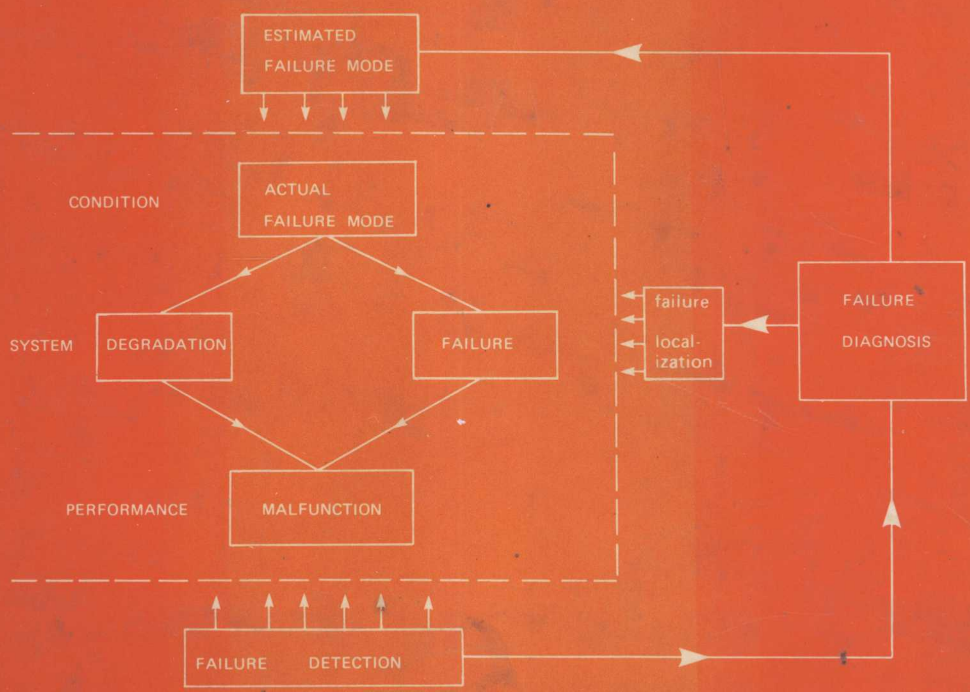
CONTROL AND SYSTEMS THEORY Volume 11

Failure Diagnosis and Performance Monitoring

L.F. Pau



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PREFACE

The main theme of this text is the application of different methodologies to the surveillance of a nondigital system (or device) or of a control system throughout its entire operating lifetime so as to obtain a diagnosis of failures and deteriorations and increase the operational availability. The term surveillance is meant to include the processing of all data records (of whatever nature) taken during the fabrication, testing, or maintenance of the equipment as well as data obtained from the monitoring of system parameters during its operation. It is important to stress here that the methods described presuppose the exclusive utilization of nondestructive tests or sensors which do not affect the system's functioning.

A second theme of this book is the generalization of the concept of failures to include classes of degraded performance. Within the framework of continuous equipment monitoring it is generally insufficient to characterize a breakdown by an excessive value of just a single functional or maintenance parameter. Physical failures or breakdowns may also result from the joint occurrence of deviations of several such parameters, with all the parameters remaining within specified tolerance values. To the notion of automatic classification of these deviation vectors one can quite naturally relate concepts of equipment condition and classes of degraded performance.

This enables us to envisage connecting the monitoring device to a condition indicator which activates an alarm whenever the level of degraded performance drops too far. The use of such indicators complies with the requirements of on-line failure diagnosis and leads to a notable increase in the safety and availability of the equipment to which they are connected.

Another objective of this book is to provide tools whereby one can systematize the process of improving the design and characteristics of a device on the basis of quantitative and qualitative information obtained during its operational life span. As a general rule, the manufacturer does not know the true behavior of the equipment under operational conditions. Therefore this information cannot be used for design or maintenance purposes. Reliability and maintenance data banks are one of the elements making up this feedback loop. It is necessary to process their contents and to have a useful and easily addressable format. Certain methods described here will address these concerns, and provide tools and solutions.

It is important to underscore the fact that the methods described here do not generally permit the immediate localization of faulty components. Initially, it is usually possible only to identify or diagnose the failure or degradation modes (taking into account the operating conditions and the operational environment). One can then usually proceed with failure localization once the failure mode is known. The most convenient procedure for this involves going through a failure search tree, complying with procedures contained in the maintenance instruction manual pertaining to the failure mode determined from initial analysis. A study of such search sequences, and of questionnaires, is contained in Chapters 4 and 5.

Rather than detailing the technology of the diagnosis or test devices, we shall stress numerical methods and diagnostic system architectures. Most of these are presented here for the first time. They have wide applicability in special-purpose digital or hybrid processors for the monitoring and diagnosis of lowered performance levels of nondigital equipment or control systems and in the partial automation of testing and quality control. The experiments and practical setups designed by the author have made possible, to a large extent, the validation of the approaches we have mentioned. The main applications would appear to be, on the one hand, within the domain of equipment for which the operational availability factor is primordial (i.e., aerospace systems, nuclear power station equipment, rotating machinery) and, on the other hand, for devices used to accelerate maintenance and repair (i.e., maintenance recorders, automatic test systems for mechanical or electromechanical equipment). Prospects are also promising for partial automation of quality control and automated monitoring of industrial processes.

Close parallels between the approaches we have outlined and the motivations behind the development of diagnostic aids and monitoring systems in medicine have convinced us that our methods may also have some utility in medical research.

This text incorporates practical considerations and also theoretical contributions from pattern recognition, reliability theory, automatic control, and mathematical statistics. Numerous practical and theoretical questions are discussed and should motivate further research. This book has been designed so that the prerequisite knowledge required includes only a general engineering background and some notions of signal theory, probability, and automatic control. However, mathematical detail has not been spared in certain parts of the text. Chapter 1 covers much of the more elaborate background material required. In Chapter 2 we define the basic notions involved in failure or degradation analysis and in performance monitoring and the constraints on the class of nondigital systems for which the techniques to be described actually apply.

Before considering the analysis of degradation data for purposes of failure detection or diagnosis, it seems logical to present models for the physical and performance degradation in those classes of nondigital equipment specified earlier. This is done in Chapter 3.

In Chapters 4 and 5 we deal with a comparison of tests from the point of view of efficiency in failure localization and diagnostic performance. The latter issue is a very important one which affects the benefits to be expected from an automated diagnosis system. The methods presented can be used to evaluate the tests and signals proposed by the technicians who are most familiar with the equipment under study.

Contemporary concern with reducing overall maintenance costs has given rise to many attempts to implement systems that evaluate equipment behavior under operational conditions, either with simple maintenance reports or with more involved forms of computerized data (as described in Chapter 6). Note that even when the problems of data collection, file updating, and file management have been solved, it may still be impossible to use properly all the information available. Methods for data analysis and data display are given in Chapters 7 and 8. Applications discussed in Chapter 9 show that it is possible to obtain diagnostic information from these files which may be used to modify the equipment or the operational conditions. Another important area of application of these methods is the comparative study of different types of equipment in operation, including the case of prototype evaluation.

In Chapter 10, we consider the relationship between pattern recognition and the automation of failure or degradation diagnosis in the static case. The procedures presented have led to operational implementations. Attention is given mainly to the diagnosis of failures and to follow-up procedures in a production line as well as to the concept of quality control throughout the fabrication process.

In Chapters 11-15 we deal with performance monitoring and failure diagnosis when dynamic measurements on the system are available. After recounting the different methodologies of internal and external diagnosis, an effort is made to develop original methods which, when combined with classical techniques of signal processing and classification, enable implementation of automatic diagnosis in important classes of nondigital equipment and control systems, such as those discussed in Chapter 2. Chapter 13 is devoted to on-line acoustic and vibration monitoring.

If the diagnosis can be made in an adaptive manner on a continuous basis that allows compensation for natural wear and the like, it is then possible to implement "on-condition" maintenance procedures or to modify equipment tasks so as to correspond with the actual condition of each system. This provides a notable improvement with respect to the arbitrary approaches normally used in choosing maintenance procedures such as periodical overhauls and random replacements. Using the example of aircraft engines, we establish methods in Chapter 15 that are appropriate for adaptive diagnosis and that can also serve as preventive alarms warning of the probable occurrence of certain degradation modes considered to be unacceptable.

In Chapters 14 and 15 we also discuss design concepts for fault-tolerant control systems and redundancy management based on failure diagnosis. This includes the case of sensor reconfiguration and filtering-based fictive sensors, and failure localization in the presence of feedback.

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Ecole Nationale Supérieure
des Télécommunications

L. F. Pau

NOTATION

$\triangleq$	definition equation
#	little different from
■	end of result or example
$\in$	belongs to
$\forall$	for all
$\cap$	set intersection
$\cup$	set union
Card(•)	cardinal, or number of elements of a set (•)
dim(•)	dimension of a vector or of a matrix (•)
det(•)	determinant value of a matrix (•)
I	identity matrix
$\otimes$	tensor product (matrix) of two vectors
$f \circ g$	operator, function, or matrix obtained by composing together the operators, functions, or matrices f, g
Pr	probability
$\hat{x}$	sample-based estimate of x
$\lVert \cdot \rVert$	Euclidean or otherwise specified norm
$\mathcal{J}(\cdot)$	integer part of (•)
$p = 2\pi jf$	complex variable p in the Laplace transformation
A/B	conditional statement A if B
p.d.f.	probability density function
f^{-1}	inverse of operator f, or inverse table look-up
$[a,b)$	interval $a \le x < b$

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FAILURE DIAGNOSIS AND PERFORMANCE MONITORING

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