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PATTERN RECOGNITION IN MAINTAINING RELIABILITY

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Abstract

In the paper a feedback control scheme for running and maintenance of industrial equipments is developed, where only input and output signals of the control loop are observable, the actual state of the system will be estimated from the output signals using pattern recognition. Technical and statistical expertise in the control loop are separated, therefore appropriate statistical tools and problems (classification, feature extraction, life statistics) can be individually accessed. The phenomenon of aging is modelled by random transitions among parameter classes with different failure rates. Optimization is reduced to a Markovian decision process. Concrete technical examples illustrate the relevance of the model.

Keywords: reliability control, maintenance policy, pattern recognition.

1. Introduction

The maintenance policy of technical equipments, focussed on increasing reliability and rentability, tends to be supported by mathematical considerations, e.g. ASHER and FEINGOLD (1984), BALOGH, DUKÁTI and SALLAY (1980), GNYEGYENKO, BELJAJEV and SZOLOVJEV (1972), MARTZ and WALLER (1982). Running as well as maintenance can be based on control principles.

Running is aimed at influencing the *state of operation* (or *state*) while maintenance is the *state of quality* (or *condition*), actually the sets of quickly changing (*operational type*) and slowly changing (*parameter type*) system variables, respectively.

As a simple example, we can consider a car. For the first type of variables we can take the speed of the car, while for the second one the cleanness of spark plugs or the pressure of air in the tyres. A carbonized spark plug can give spark, a soft tyre with higher rolling friction can roll, but the car needs more fuel than usual. Apart from decrease of rentability, as the above mentioned parameters deteriorate, the chance is growing that the motor gets out of gear or the tyre gets punctured.

The problem to be solved is the analysis of slow and abrupt changes: their connection, forecast, for some of them prevention. Classical methods of analysis can be found e.g. in the textbooks ASHER and FEINGOLD (1984), GIHMAN and SKOROHOD (1979).

We suggest a reliability control model which is applicable for a large number of technical equipments and is motivated by state space methods of system engineering, reliability based maintenance theory and mathematical pattern recognition.

2. The Underlying Control Loop

Suppose that we have some technical equipment whose behaviour is described by the *system equation*

$$\Phi(\mathbf{x}, \mathbf{u}, t) = \mathbf{0} \tag{2.1}$$

and the output process by the *output equation*

$$\mathbf{y} = \Psi(\mathbf{x}, \mathbf{u}, t). \tag{2.2}$$

Here we have the following notations:

$\mathbf{x} \in \mathbf{R}_n$ the vector of system state variables (function of time);

$\mathbf{u} \in \mathbf{R}_m$ the vector of control variables (function of time);

$\mathbf{y} \in \mathbf{R}_k$ the vector of output variables (function of time);

t the system time;

Φ and Ψ vector valued operators on the space of $n+m+1$ dimensional time functions.

$\mathbf{u}$ serves as input signal for the system, while $\mathbf{y}$ is the output signal, i.e. the system response. After an evaluation of $\mathbf{y}$ a new input signal is generated which tries to force the system to produce a 'better' output signal. Input may have a noise and the system may work in a stochastic way.

This is a common feedback control loop which is valid for a very broad class of control problems, see e.g. the textbooks DAVIS and VINTER (1985), GOODWIN and KWAI (1984), ISERMANN (1981).

For theoretical investigations it is generally assumed that the structures of Φ and Ψ are more or less known, and one can — again more or less — find out the values of $\mathbf{x}$ and the essential parameters of Φ and Ψ. Real life systems are mostly black boxes for us where we can measure input and output signals but we have hardly a guess about what happens inside.

This is why we make no further assumption on the nature of Φ and Ψ. In what follows we try to give a methodology to base our control policy on statistical analysis with the incorporation of engineering expertise.

3. Quality Classes and their Transition Probabilities

Let the system state vector have the decomposition

$$\mathbf{x} = (\mathbf{v}^T, \mathbf{w}^T)^T, \ \mathbf{v} \in \mathbf{R}_q, \ \mathbf{w} \in \mathbf{R}_{n-q}, \tag{3.1}$$

where $\mathbf{v}$ represents the state of quality and $\mathbf{w}$ the state of operation.

Suppose that we have a group of disjoint subsets in $\mathbf{R}_q$, denoted by $V_1, \ldots, V_r$. Each of these subsets corresponds to a parameter vector set representing a *quality class* (technical characteristic, proper state and/or operation) of the system.

Each quality class has its own system equation

$$\Phi_i(\mathbf{x}, \mathbf{u}) = \mathbf{0} \qquad i = 1, \ldots, r \tag{3.2}$$

and output equation

$$\mathbf{y} = \Psi_i(\mathbf{x}, \mathbf{u}) \qquad i = 1, \ldots, r, \tag{3.3}$$

where Φ_i and Ψ_i are real vector valued operators on the space of real $n+m$ dimensional time functions.

Note that (3.2) and (3.3) correspond to (2.1) and (2.2) but the explicit dependence on time has disappeared. This can be done using the concept of quality classes. Namely, the full life of the system is divided into a finite number of periods, each having its own equations (3.2) and (3.3).

Note also that using the decomposition (3.1) quality class is determined by $\mathbf{v}$ but this does not mean that $\mathbf{v}$ cannot change while the system spends some time in this class. (In our simple example with the car this may correspond to a slight decrease or increase of tyre pressure which has, however, no remarkable effect on steering or dynamics of the car.)

Transitions between quality classes may have two forms. Forced transitions happen following appropriate control actions. Random transitions happen at the end of a random sojourn time in a quality class. (As for the car, examples for the two forms of transition are: pumping up a soft tyre and an unexpected puncture, respectively.)

We will suppose that the system spends an exponentially distributed time in any quality class if no forced transition happens during the sojourn. The reason for this assumption is that the essential properties of the system do not change during the sojourn in the given class — this is the way quality classes are defined — therefore departure time from the class does not depend on the time spent in this class.

The class the system arrives at after a spontaneous transition is randomly chosen by the system because in real life situations there may be both different kinds of deterioration (in most cases) and improvements (rarely).

Let $\mathbf{x}(t) = (\mathbf{v}(t)^T, \mathbf{w}(t)^T)^T$ be the time function describing the system state. We define the event

$$A_i(t) = \{\mathbf{v}_i(t) \in V_i\}. \tag{3.4}$$

We introduce the nonnegative numbers λ_i, $i = 1, \dots, r$ and ν_{ij}, $i, j = 1, \dots, r$ for the following model of transitions:

$$P(A_i(t + \Delta t) | A_i(t)) = 1 - \lambda_i \Delta t + o(\Delta t), \tag{3.5}$$

$$P(A_j(t + \Delta t) | A_i(t)) = \lambda_i \nu_{ij} \Delta t + o(\Delta t). \tag{3.6}$$

We allow zero values for some λ_is because there may be quality classes that the system is unable to leave spontaneously. These correspond to different failure types when running is possible only after repair, i.e. forced transition. (In our example: unexpected puncture of the tube pushes us into such a class because we can leave it only by either changing the wheel or repairing the tyre. We note that by changing the wheel we get into a degraded state since we use the reserve to the forced transition.)

For the connection between the pre-transition and post-transition values of $\mathbf{x}$ (normally a conditional distribution function) we do not supply here any model. We need and require only that this connection is stationary in time which is a reasonable assumption.

We point out here that this model is able to express reliability changes. High, medium and low reliability correspond to low (but positive!), medium and high λ_i values, respectively. If ν_{ij} values are higher for less reliable and failure classes in j then the system tends to lose reliability if no forced class change happens, which means simply aging. It is very important that this is described through a stationary model. (Returning to our example this corresponds to the process when the tread of the wheel gets into gradually lower quality classes because of attrition or fissures due to aging of the tyre. From these classes we reach sooner other classes corresponding to failures. The reasons may be: nails or glass splinters can more and more easily punch first the tyre then the tube; the car has a growing chance to skid; the tyre can be damaged more and more easily when jumping onto the kerb or because of friction at parking too close to the kerb.)

4. The Concept of the Control Model

We consider the system from outside. We can observe only $\mathbf{y}$ but not $\mathbf{x}$. In general it cannot be supposed that the system is observable (i.e. $\mathbf{x}$ can be computed from $\mathbf{u}$ and $\mathbf{y}$). It cannot be supposed even that the system is identifiable because we normally do not know the operators Φ_i.

In order to control the system we need, however, some information on the system state.

We call the system *classifiable* if from the trajectory of $\mathbf{y}$ we can determine the quality class by means of some classification algorithm, at a probability level which is satisfactory in some sense.

Suppose now that our system is classifiable. Let the result of the classification be class index j. If we are happy with this value, we can proceed. If not, we force the system to change class (e.g. by means of a repair). This is the job of the *state dependent maintenance*, see e.g. CHOWDHURY (1986), EICHLER (1982), ROSS (1970).

At this point we can make 'fine tuning' of the system through an appropriate choice of $\mathbf{u}$. The word 'fine' is understood of course in a relative sense because on the one hand we know neither the state vector nor the state equation, on the other hand our control action may be seriously distorted by environmental effects, making the system input very noisy.

Then we observe again $\mathbf{y}$ and the control cycle is closed.

As for the objective function: all class changing and fine tuning activities together with pattern recognition may have costs while proper values of the output vector may deliver profit and improper values again cost. For cost analysis and objective function construction see e.g. CHOWDHURY (1986) and COLLANI (1989).

What we finally get is a controlled Markovian process to be optimized, i.e. a Markovian decision process. This topic is covered by the textbooks ROSS (1970) and GOODWIN and KWAI (1984).

The question arises: what other statistical methods can be used in this control model.

In general, it is not the output vector itself that is directly classified. The object of classification may contain information from a couple of consecutive observations. Therefore dimension reduction is an indispensable requisite of classification. This is a feature extraction activity which is partly pure statistical analysis, partly, however, a matter of engineering expertise.

It is also a problem to estimate the numbers λ_i and ν_{ij}. The trouble is that statistical classification delivers a result only at a probability level less than 1, therefore in the estimation process we use a number of improper observations.

A widely used tool of quality control has an interesting connection with this model. The values plotted on a control card deliver actually output vectors. Frequency and concentration of dots within and beyond acceptance limits are the result of a feature extraction procedure. Finding the reason of deviation from 'good' values is a classification activity. Measures taken afterwards to restore normal operation are control interventions. Statistical Process Control may therefore be considered as a 'simple' version of the above mentioned control model. (Some elements of this approach can be found in MONTGOMERY (1990)). This statement can, however, be reverted. The two dimensions available in a plane constitute a limit for the extension of control cards toward recording multidimensional data (there have been experiments with such extended control cards, see MONTGOMERY (1990), but with poor results). Pattern recognition may serve to fill in this gap, because computers can easily store multidimensional data and analyze their spatial location.

5. On Possible Applications

Technical practice shows some examples where the above mentioned principles have been fully put into action, but partial applications also show the possibility of widespread utilization. On the maintenance of the most advanced technical systems, however, it has been published very few compared to what actually exists — due to military or business secrecy.

Partial applications of the above principles are e.g. *state inspection of belted conveyor* using computer video picture processing, see LINGS and RODD (1987), or *fault analysis by robot* introduced by Ford Motor Company in 1986, see GORMAN (1987). Its proliferation is explained by the fact that high technology develops faster than the expertise of workers using it.

Reliability Control in Equipments of Industrial Electronics and Automation

The Thermal Power Station and Servicing Enterprise of the Csepel Metallurgical Works has introduced an off-line reliability control system as result of a development cooperation with the Department of Precision Engineering and Optics of the Technical University of Budapest, see SCHÖNFELD (1985).

From the point of view of maintenance, determining system reliability on the basis of *a priori* models and computations is not reasonable in case of large engineering equipments since these are mostly individual and largely complex hence computational costs are not in accordance with the profitability of results. Continuous check and prediction of system reliability are made possible by reliability tests under factory circumstances.

An essential feature of the method applied was that it controlled faultless operation on the basis of failure rate, as on possible representation of the chosen characteristic. This choice was motivated mainly by the fact that measurement of empirical values of failure rate could be easily carried out in practice and a great part of the control loop could be made object independent. This shows the way toward practical implementation because it fills the gap between classical methods adequate for mass production and the problem of quality control for individual equipments.

Technical Diagnostics of Autopilots through Pattern Recognition

In the course of the traditional technical diagnostics of the autopilot BAP6 of the passenger aircraft TU–154 more than 100 measurements had to be carried out. Using mathematical pattern recognition (see TÓTH (1980)) the number of necessary measurements could be decreased to one tenth of the original. A special feature of the solution was that the so-called risk matrix is antisymmetric. This expresses the fact that we commit a more serious mistake by qualifying a faulty equipment good than by sending it to an unnecessary repair. In the language of mathematical statistics: an error of the first kind endangers the safety of the aircraft while an error of the second kind causes only increased maintenance costs. We have to mention, however, that an unnecessary repair itself may be the starting point of later failures so this kind of error must be also reduced.

In the course of solving the problem feature extraction and formation of the pattern vector took place on the basis of technical considerations. Having tested some pattern recognition methods one of them emerged as reducing the error of the first kind to zero while keeping the error of the second kind at a level not endangering rentability. The tool was the program RECO, see BARTA *et al.* (1987–1990), developed at the Department of Precision Engineering and Optics of the Technical University of Budapest and supported by the Hungarian National Committee for Technological Development.

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