Information and analytical support for technical monitoring systems with a multi-level structure⋆

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Abstract

The article is devoted to the study of the problem of forecasting the load at the input of a multilevel monitoring and diagnostics system, as well as assessing the residual resource of complex technical objects that are in an unregulated state. The dynamics of the development of each unregulated state is described by a separate model based on control data. The relevance of using a polyharmonic model, which allows for seasonal, cyclical, and stochastic fluctuations in the input information flow, is considered. The use of a combination of harmonic analysis with an autoregressive component is proposed to refine the forecast, taking into account the random component.

The task of selecting a maintenance strategy based on game theory has been formalized, in particular using the payment matrix method, which takes into account the costs and benefits of applying different strategies. It is proposed to structure the mathematical support of the multilevel monitoring and diagnostics system by individual units: forecasting the input load and assessing the remaining resource with the selection of a response strategy. The presented approach allows for a systematic approach to the diagnosis of the technical condition of objects and increases the efficiency of the entire multi-level monitoring and diagnostics system.

The research results can be used to develop effective real-time dispatch algorithms, particularly in transport, energy, and industrial infrastructures. The proposed approach takes into account the dynamic variability of object states and minimizes losses from untimely maintenance.

Keywords

automated control systems, multi-level monitoring and diagnostic systems, adaptive multi-level monitoring and diagnostic systems, performance evaluation, least squares method, control, diagnostic, forecasting and decision-making subsystems.

1. Introduction

In the field of research into multi-level monitoring and diagnostics systems (MMDS) for complex technical objects, particularly for mass service systems (MSS), there has been active development of both applied and theoretical approaches in recent years. MSS with a multilevel structure for monitoring and diagnosing complex technical objects play a key role in ensuring the reliability and continuity of critical infrastructure facilities [1, 2]. Given the increasing complexity of technical systems and the requirements for rapid detection and prediction of failures, there is a need for improved mathematically sound methods for analyzing their operating modes.

The paper [3] considers the application of multilevel systems for solving the problems of monitoring and diagnostics of electrical equipment. The authors analyze the effectiveness of building a multilevel architecture using the example of energy facilities. The advantage of this work is its practical focus, but there is no detail on decision-making algorithms.

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In [4], a method for real-time failure detection based on multi-channel fusion of sensor data is developed. The approach allows for high accuracy but is focused only on short-term control, without predicting the remaining resource.

Article [5] is devoted to the application of IoT architecture for remote equipment monitoring. A scalable system with cloud processing is proposed. The main advantage is flexibility and integration with the Internet of Things, but the study does not cover highly complex industrial facilities.

Publication [6] discusses the detection of anomalies in multi-level monitoring systems in multi-cloud environments using large language models. This approach demonstrates high adaptability, but requires significant computing resources and is not adapted to physical technical objects.

Work [7] proposes an analytical platform for multithreaded monitoring in production systems. The authors use principal component and control chart methods. The strength of the work is the processing of large data sets, while the weakness is the limited implementation of adaptive elements.

Study [8] focuses on uncertainty management in multi-level diagnostics of technical equipment. Although the example is somewhat outdated, the approach to processing probabilistic information is relevant and can be adapted to modern systems.

Finally, [9] proposes a quality monitoring method for laser cladding processes based on a single sensor with multilevel processing. The method is economical and highly accurate, but has a narrow application range.

Thus, the analyzed sources indicate the relevance and versatility of the problem of building MMDS. The analysis shows that MMDS are increasingly being considered as a viable solution for tracking parameters and assessing technical condition in complex and highly stressed technical environments. Much of the recent research focuses on multi-level data monitoring, real-time analysis, and intelligent decision-making.

An analysis of contemporary sources indicates a high level of interest among the scientific community in the development of multi-level monitoring and diagnostic systems in complex technical conditions. The leading areas include:

- development of reliability prediction methods;
- implementation of intelligent failure detection systems;
- use of highly sensitive sensors;
- fusion analysis of data from multiple sources;
- construction of digital adaptive platforms.

However, there are still a number of shortcomings:

- limited attention to adaptive behavior in dynamic service environments;
- insufficient large-scale industrial validation;
- computational complexity of some of the proposed solutions.

Future research should prioritize hybrid architectures that support predictive resource assessment and demonstrate adaptability in service-oriented infrastructures, such as transportation and manufacturing systems, as well as for a class of complex industrial facilities (hydroelectric power plants, thermal power plants, nuclear power plants) [1,10].

The purpose of this work is to present a theoretical game-theoretical approach to analyzing the functioning of a diagnostic subsystem that operates on a cyclical monitoring and maintenance principle. This approach allows us to investigate the probabilistic structure of the movement routes of the service device in the system, taking into account delays in monitoring, diagnostics, and data transmission, and provides the selection of the optimal management strategy based on polyharmonic analysis and a theoretical game approach to performance evaluation. Particular attention should be paid to the assessment of losses associated with untimely maintenance of objects, which is critical for building adaptive real-time dispatching algorithms.

To achieve this goal, the following scientific tasks must be solved:

-analyze models for predicting the development of unregulated states and assessing the residual resource of complex technical systems;

- justify the relevance of using a polyharmonic model to predict the intensity of the incoming flow of requests to the MMDS, taking into account the cyclicality, seasonality, and stochastic nature of the processes;

- formalize the task of selecting an MMDS operating strategy using the payment matrix method, which takes into account the probable scenarios of object states;

- implement an approach to selecting the optimal strategy using game theory methods and optimization objective functions (maximizing effect or minimizing costs).

2. Forecasting, resource assessment, and strategy selection in technical monitoring systems

2.1 Forecasting the load on the MMDS input based on a polyharmonic polynomial, taking into account the stochastic component

The relevance of forecasting in MMDS is determined by the need to forecast the load at the system input based on data from all objects of man-made systems, as well as to assess the remaining resource of a specific complex technical object that is in an unregulated state.

Given the cyclical nature of technological operations and the seasonality of phenomena caused by changes in natural cycles, temperature regimes, and weather conditions, the most adequate model for forecasting the intensity of the input flow of requests at the MMDS input is a model described by a polyharmonic polynomial represented in expression [2]:

$$P_i(t) = a_0 + \sum_{i=1}^{n} \left(a_i \cos\left(2\pi K_i \frac{t}{N}\right) + b_i \sin\left(2\pi K_i \frac{t}{N}\right)\right) + d_0 + d_1 t \quad (1)$$

where n is the number of harmonics in the model training period N K_i; – is the coefficient that determines the harmonic number (*i=1,...n; n=N/2*); *t* is the time interval number, *t=1,2,3* The model coefficients a_0, a_i, b_0 are the mean statistical estimates of the Fourier coefficients [11] for the time series of parameters obtained experimentally, and the coefficients d_0, d_1 are the mean statistical characteristics of the trend. All model coefficients are determined using the least squares method [12]. According to the values of vector Y – vector of initial values, ,$Y=\{y_1, y_2, \ldots y_i, \ldots y_n\}$ each embedded automaton in the simulation subsystem selects and configures the corresponding time series model $P_i(t)$ of a complex technical object in the form of a polyharmonic polynomial (1).

The output signal of the model corresponding to the generalized parameter for P* time t is defined as the superposition of simulation signals $P_i(t)$ *(i=1,...n)*:

$$P^*(t) = \sum_{i=1}^{m} P_i(t).$$

To refine the global forecast, model (1) is supplemented with a forecast of the random component, which is generated based on the autoregression equation. To automate the synthesis of an adequate model, an iterative procedure and algorithm can be developed that allow, based on the sequential complication of the model by supplementing it with a sequential series of harmonics, to synthesize a model of optimal complexity in accordance with the following criteria: the criterion of stochasticity of fluctuations in the levels of the residual sequence, the criterion of normal distribution of the random sequence of the residual component, the criterion of equality of the mathematical expectation of the random sequence to zero, and the criterion of independence of the values of the random sequence (the Darbin-Watson criterion) [13, 14].

Analysis of models for predicting the development of unregulated states and assessing residual resources showed that these models can take the form of first-, second-, and third-degree polynomials. At the same time, the dynamics of each unregulated state is usually described by a new model, the form of which is determined in the process of controlling the unregulated state. The section is devoted to the problem of forecasting the load on the MMDS input in complex man-made environments. It describes a polyharmonic model that takes into account the periodicity, trend, and stochastic fluctuations in the input data. Forecasting is refined by modeling the random component based on autoregression and applying adequacy criteria.

2.2 Assessment of residual resources and selection of optimal restoration strategies based on a theoretical game model

Formalization of the task of selecting an MMDS strategy allowed reducing it to a game theory task, in which the strategy randomly sets the characteristics of an unregulated state, and the decision-making subsystem selects its own optimal strategy for restoring the state of objects. The strategy selection model is presented using the $n*m$ payment matrix method C [15]. The rows of the matrix correspond to MMDS strategies, and the columns correspond to the predicted intensities of unregulated states for the ΔT period.

Each element of the matrix contains an assessment of the effect corresponding to the economic (or other) effect ef_{mn} for a specific strategy, represented as a fraction e_{ij}/z_{ij}, the numerator of which characterizes the expected gain (e.g., saved resources or reduced risk), and the denominator is the i-th cost of applying the strategy when eliminating the j-th unregulated state ($i=\overline{1,n}, j=\overline{1,n}$). That is:
where C is an $n \times m$ payment matrix, ef_{ij} is the effect (gain) of applying strategy i in the predicted state j; e_{ij} is the expected quality (gain) z_{ij}; is the cost of applying the i-th strategy to the j-th state (predicted intensities or failure scenarios over the interval ΔT), $i=\overline{1,n}$ is the MMDS strategy index

$$C = [ef_{ij}]_{m\times n}, \quad ef_{ij} = \frac{e_{ij}}{z_{ij}},$$

(matrix rows); $j=\overline{1,n}$ - index of the predicted intensity of the unregulated state (columns of the matrix).

Criterion for selecting the optimal strategy: the selection of strategy $s \in S$ is made taking into account the conditions of each task, for example, based on maximum efficiency or minimum costs, taking into account the following expressions:

Similar approaches to modeling strategic choices under uncertainty are actively researched in contemporary works on reliability analysis, technical resource forecasting, and decision-making game models [16, 17]. This section logically continues the analysis of forecasting tasks in the context of assessing the residual resource of technical objects in an unregulated state.

$$s = arg \max_{s_i \in S} \sum_{j=1}^{m} ef_{ij} \quad \text{або} \quad s = arg \min_{s_i \in S} \sum_{j=1}^{m} z_{ij}.$$

The study found that the dynamics of the development of unregulated states of complex technical objects can be effectively described using polynomial models of varying degrees of complexity. Formalization of the process of selecting the MMDS functioning strategy using the payment matrix method made it possible to structure the decision space and take into account the economic efficiency of each of the alternatives. The application of game theory methods provides the possibility of adaptive strategy selection, taking into account the variability of technical condition scenarios. The proposed approach has high potential for integration into digital maintenance platforms, especially in industrial environments focused on real-time diagnostics.

Declaration on Generative AI

During the preparation of this work, the authors used Grammarly in order to grammar and spell check, and improve the text readability. After using the tool, the authors reviewed and edited the content as needed to take full responsibility for the publication's content.

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