Monitoring and Controlling Condition of Complex Multiparametric Object

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Abstract. Technology is advancing ever faster in all areas of human activity, making the objects around us ever more complicated. Notably, complex objects have multiple parameters that define their condition, whether normal, near-critical, critical, over-critical, etc. If critical infrastructures are in critical condition, their collapse jeopardizes not only the infrastructures, but also their environment. This is why timely maintenance and control of condition is imperative for complex objects. This paper dwells upon a method for monitoring and controlling the condition of a complex multiparametric object; the method uses a minimum number of monitored parameters to retain full data on the condition of a complex object, to optimize the periodicity of taking readings depending on the functional phase of the object, and to determine how object parameters relate to each other and how they affect the quality of its functioning; such minimization reduces computational complexity and the bandwidth requirement. Russian Invention Patents granted to the authors certify the novelty and practical significance of the proposed solution.

1. Introduction

Technology is advancing ever faster in all areas of human activity, making the objects around us ever more complicated. Virtually every piece of technology today, be it a phone, a coffee machine, a rocket or a communication network, features an automatic control system (ACS). There are ever more objects that run ever more functions, which compromises their reliability, especially if external destructive factors are brought into equation. Notably, complex objects have multiple parameters that define their condition, whether normal, near-critical, critical, over-critical, etc. If critical infrastructures are in critical condition, their collapse jeopardizes not only the infrastructures, but also their environment. This is why timely maintenance and control of condition is imperative for complex objects. The effectiveness of monitoring and controlling the condition of a complex object directly affects the quality of its functioning [1, 2].
2. Overview of the existing methods for monitoring complex objects

The existing monitoring systems designed for complex multiparametric objects include instrumentation and telemetry systems, automatic or automated instrumentation complexes, etc., which usually contain an instrumentation and alarm subsystem, a communication subsystem, and a supervision subsystem.

The following approaches apply to monitoring and supervise the condition of such objects [3, 4, 5]:
- continuous condition reporting at a specified update rate, whereby data can be but is not necessarily timestamped;
- generating events when a change in condition is detected, e.g., if a reading or the delta of two consecutive readings exceeds a certain threshold, whereby such event reports contain the measured value and are timestamped.

Data produced by the first approach resolves very well if the update rates are higher than the rate of change in the monitored parameter; however, it is also redundant in steady operation, as new data tends to contain no useful new information. Besides, it requires a substantial bandwidth in communication channels. The extreme case is continuous oscillography of the waveform of the parameter-specific input signal. Reducing the update rate compromises the resolution and may even cause some fast processes to be missed completely.

The second approach requires detecting change in the condition of the monitored object; it generates less data. Event generation criteria, e.g., the thresholds in the monitored parameters, are what determines the resolution of data.

There are combined implementations where a change in the condition triggers an event and starts waveform logging.

Many Russian and international researchers work on improving these approaches and developing fundamentally novel control and fault detection algorithms: S.A. Basharin, S.A. Bukashkin, D. Bendler, P.A. Butyrin, A.M. Vinogradenko, V.A. Gulyaev, P.S. Davyдов, N.S. Danilin, L.V. Danilов, K.S. Demirchyan, O.I. Kazakov, N.V. Kirscht, V.P., Larin, A.A. Lanne, L. Leung, , P.N. Matkhanov, V.G. Mironов, Yu.I. Starodubtsev, A.E. Salama, Yu.D. Sverkunov, B.Ya. Sovetov, Ye.B. Solovьyova, P.G. Stakhив and others.

However, it would be premature to talk of creating a complete control and monitoring method that could handle a complex multiparametric object and serve as a foundation for state-of-the-art monitoring and control systems.

The majority of today’s monitoring and control systems are associated overloaded controls and automations, time-intensive measurements and evaluations, and the need to use costly equipment and involve high-skilled staff.

3. Monitoring and controlling the condition of a complex multiparametric object: statement of problem

Continuous monitoring of all the parameters of a complex object requires substantial computing and networking capacity coupled with minimum delay in response to a change in the monitored parameters (i.e., change in the condition of the object). With these in mind, the cost of monitoring and control automation systems can be exorbitant.

Thus, there is a need for new condition monitoring and control system that would help optimize the periodicity of taking readings from complex objects, take into account the informativeness of such parameters and the destabilizing factors to determine the condition, the relationship between the parameters, and how they affect the condition of the objects and thus the quality of its functioning, functional phase-specific the rate of change in the parameters of objects and their elements, the resources of the monitoring and control automation system, etc.

4. Monitoring and controlling the condition of a complex multiparametric object

Fig. 1 shows the key steps of monitoring and controlling the condition of a complex multiparametric object.
**Step 1.** Preparing input data.
Implementation of the proposed method requires the following input data:

- a set of approximants that meet the specified requirements (namely, they must be harmonic functions);
- approximation accuracy $\varepsilon_{\text{aa}}$, which determines whether harmonic functions could be used to approximate the characteristic of a parameter of the complex object over a timeframe. It also serves as the criterion for changing the approximant to approximate the characteristic of the parameter in general [6];
- limits and increments/decrements of the approximant parameters [6];
- $N$ states of the complex object and $M$ parameters that describe its condition (states and parameters can be presented based on the results of simulation, design, and manufacture, or empirical operating data; the values of the parameters should define the status or condition of the complex object. Citing the example of a communication network, it can have the following status: offline, running normally, running on peak, running under near-critical load, critical condition (recovery possible), over-critical condition (recovery impossible). For this example, the condition parameters could be throughput, data transmission lag, optical fiber degradation, utilization of the computing capacity of the automatic control system, etc.);

![Figure 1](image-url)

**Figure 1.** Key steps of monitoring and controlling the condition of a complex multiparametric object.
– $R$ possible internal and external destabilizing factors $K$ parameters thereof. For example, in a telecommunication network, any physical or technological process, whether internal or external, can be considered a destabilizing factor if it causes elements of this network to fail [7]. According to [7], destabilizing factors fall into external and internal ones. For a telecom network, factors originating outside the network are external. External destabilizing factors a further subdivided into mechanical impacts (a seismic shock, an explosion shockwave, a ballistic shock), electromagnetic impacts (LF or HF radiation, UHF radiation, an electromagnetic pulse); ionizing impacts (alpha, beta, and gamma radiation, neutron radiation); and thermal impacts (light radiation from explosion). Internal destabilizing factors originate inside a network, and there is enough data on the impact they could have to effectively localize such factors and take any necessary preventive or reparative measure at any stage from design and manufacture of equipment to the design and operation of the entire network. Most common internal destabilizing factors are: the quality of electrical contacts; the aging of electric radio components, which tend to change their parameters over time; loss of electromagnetic compatibility due to failed shielding, grounding, or filtering, which makes the equipment more susceptible to electromagnetic interference; and power outages. Here are some examples of parameters that could describe a destabilizing factor: wave amplitude, its speed (acceleration), the duration of a pulse (number of phases per pulse), etc., for a seismic wave (a mechanical external destabilizing factor); changes in electric and magnetic field intensity over time (pulse shape) and their spatial orientation, as well as the maximum field intensity (pulse amplitude) for an electromagnetic pulse; frequency and intensities of electric and magnetic fields for electromagnetic radiation, etc. [8, 9, 10].

- time $t_{\text{est}}$, over which the functional condition and process of a complex object are being estimated, during which the object has to be in each of the $N$ possible states triggered or caused by $R$ destabilizing factor; for instance, if the complex object in question is an aircraft, $t_{\text{est}}$ is the duration of standard tests (ST) that subject the aircraft to all possible internal and external destructive effects such as lightning, hail, crosswind, failure of nodes and units within the aircraft, etc., in a variety of operating conditions or situations such as accelerating on the runway, landing, climbing, automatic and manual control, etc.

- time $\Delta t$ of checking $M$ parameters of the complex object; for this estimation, one can set up the worst-case scenario per [3,4];

- the functioning quality requirements.

Step 2. Estimate the functional conditions and process of the complex object over time sufficient to collect data on the object in all possible states as exposed to all possible destabilizing factors.

Estimation of the functioning conditions generates a set of data on the time and effects of $K$ destabilizing factors by measuring the values of $M$ parameters of the complex object over the time $t_{\text{est}}$. During $t_{\text{est}}$ the object has to be in each of the $N$ possible states as affected by $R$ destabilizing factors.

Individual instruments or instrumentation complexes can be used to measure the parameters. For instance, in case of a fiber optic data channel, they use: a reflectometer to measure the parameters of the linear path (the optical fiber); coherent scatter meters to detect vibroacoustic (destructive) effects on, and damage in, the optical cable; a microscope to evaluate the quality of optical fiber ends; optical power meters to measure the signal parameters; transport network analyzers to test channel equipment, etc.

Step 2. List $L$ basic parameters sufficient for monitoring the complex object.

This step determines the most informative parameters, monitoring which is enough to calculate the remaining parameters of the complex object.

To that end, find the interdependencies of $M$ parameters. That can be done, for instance, by running correlation analysis to produce various coefficients of correlation (linear, multiple correlation, Spearman rank-order, Kendall’s rank, etc.) between different parameters. Some of the interdependencies may already be known [11, 12].

Use the results to list $L$ basic parameters that can be used to calculate the remaining $H$ parameters, whereby $M \leq L + H$.

The list of basic parameters should be sufficient to calculate the unlisted parameters; at the same
time, it should not be redundant, i.e., if finding $L$ basic parameters is enough to monitor the remaining parameters from the set $M$ by calculating them, the calculable parameters should not be measured to avoid overloading the instrumentations and automations of the complex object. Basic parameters are defined the most informative parameters, i.e., their relationships are enough to calculate as many other parameters as possible.

To that end, construct a variational series of parameters ordered by the number of calculated relationships with other parameters, and sample the minimum number of parameters that is sufficient to calculate all the remaining parameters in the series [13].

Step 3. Find the optimal rate of updating each basic parameter for each functional phase of the object.

To that end, approximate the characteristics of each of the $L$ basic parameters by a set of specified harmonic approximants to the required accuracy $e_{\text{aa}}$. Approximation time for each function should correspond to the separate functional phase of the complex object for this particular parameter; change the approximant should it fail to meet the accuracy requirement.

Approximation consists in representing complex functions $s(x)$ or discrete samples of those functions $s(x_i)$ by simple and convenient approximants $f(x)$ so as to minimize deviation of $f(x)$ from $s(x)$ in its range of definition by the predefined approximation criterion.

Approximation accuracy $e_{\text{aa}}$ can be estimated by various approximation criteria. Here are the most common criteria [14, 15, 16]:

– standard approximation, where the mean squared deviation of the approximant $i = \tilde{\Phi}(u)$ from the actual dependency $i = \Phi(u)$ should not exceed the acceptable limit $\delta$:

$$\left| \tilde{\Phi}(u) - \Phi(u) \right| \leq \delta$$

in the approximation range $\Delta V = u_2 - u_1$ of the values of $u$;

– uniform approximation, where at any $u$ in the range $\Delta V$ the deviation $\tilde{\Phi}(u)$ from $\Phi(u)$ should not exceed $\delta$, i.e., $\left| \tilde{\Phi}(u) - \Phi(u) \right| \leq \delta$.

Approximation accuracy and the set of approximants consistent with the requirements are part of the input data.

According to [16], accuracy of 0.05 is normally sufficient. A lower value may overcomplicate the approximant.

In particular, with the configured accuracy $e_{\text{tr}}$ by continuous periodic functions (e.g., simple harmonic curves written as $y = A\sin(\omega_0 t + \varphi)$, $y = A\cos(\omega_0 t + \varphi)$, where $A$ is the oscillation amplitude, $\omega_0$ is the circular (cyclic) frequency, $\varphi$ is the initial phase of the oscillation. According [17], since cosine (sine) is a periodic function with a period of $2\pi$, its period $T$ can be defined as $T = 2\pi/\omega_0$.

Number of oscillations per unit time is referred to as the oscillation frequency $f$. Apparently, $f$ is related to the duration of a single oscillation $T$ by the ratio: $f = 1/T$.

Algorithms for finding approximants, including trigonometric functions, are known. For instance, paper [16] proposes the following multistage algorithm to find a trigonometric polynomial:

– set permissible error (approximation accuracy) $e$;
– set parameter variations;
– set the frequency by statistical tests; generate $j_1$ evenly distributed random numbers. Select frequencies from this set sequentially;
– for each frequency, calculate variations for individual components;
– test criterion value.

Should the approximant fail to meet the approximation accuracy requirements, find another approximant from the defined set to describe the values of the \(l\)th parameter of the complex object. Thus, approximate the values of each of the \(L\) parameters over \(t_{\text{test}}\) by \(G_l\) harmonic functions from the defined set of approximants; the approximation time for each function corresponds to a separate functional phase of the complex object for the \(l\)th parameter.

This will return the frequency and values of the function components that minimize the approximation error.

Thus, to find the optimal period of control for each of the \(L\) parameters in each phase, find the frequencies of the corresponding approximants. Next, calculate the optimal period of control for each approximant for each of the \(L\) parameters.

The step is based on Kotelnikov’s theorem, a fundamental theorem of theoretical radio engineering [18, 19].

According to the theorem, an arbitrary signal whose spectrum does not contain frequencies above \(f_s\) can be completely and unambiguously restored if there are known reference values of this signal sampled at equal time intervals \(1/(2f_s)\).

Thus, by monitoring values at time intervals equal to the ratio \(T_{\text{ctrl}}=1/(2f_s)\), where \(f_s\) is the highest frequency of the approximant, the parameters of the monitored process can be unambiguously restored for the given timeframe. Since all the approximants are uniform and harmonic, \(f_s = f\), where \(f\) is the frequency of the approximant.

Use the equation \(T_{\text{ctrl}} = 1/(2f)\) to find the optimal monitoring period for each of the \(L\) parameters in each phase as affected by various destabilizing factors.

**Step 4.** Determine the relationships between and make a list of the parameters that affect the quality of functioning.

The key properties of a complex object are all interrelated with a varying degree of correlation. Each property can be represented by several indicators. Thus, complex objects can be represented by a cyclical system of indicators, a balance ring [20], in which a change in a single indicator triggers varying change in several other indicators that describe the key properties of the complex object. Thus, any way to alter this or that indicator may help balance the whole system of indicators and attain the required quality of functioning of the complex object.

To that end, make a list of indicators that describe the key properties of the complex object and the quality of its functioning, a list of parameters needed to determine those and subject to monitoring.

Evaluate the relationships and the influence of each monitored parameter on the quality indicators of the complex object; construct variational series by ranking the parameters by their effect on the quality indicators in ascending order.

**Step 5.** Monitor the condition of the complex object

Monitor the condition of the complex object; to that end, measure the selected parameters at intervals determined at Step 3, communicate the readings for further processing, and thus determine the condition of the object and the quality of its functioning.

**Step 6.** Control the complex object.

Should the quality of functioning fail to meet the requirements, use data collected at Step 5 to find the parameter that must be adjusted by corrective action.

5. Conclusions

Thus, the presented method uses a minimum number of monitored parameters to retain full data on the condition of a complex object, to optimize the periodicity of taking readings depending on the functional phase of the object, and to determine how object parameters relate to each other and how they affect the quality of its functioning; such minimization reduces computational complexity and the bandwidth requirement. Russian Invention Patents granted to the authors certify the novelty and practical significance of the proposed solution [1, 3, 4].
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