Multicriteria assessment of optimal forecasting models in decision support systems to ensure the navigation safety

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Abstract. When developing the Decision Support System (DSS), the operability of the internal motion and maneuvering control systems of the vessel is characterized by a large number of parameters, which should be monitored in order to achieve the expected results. The task is to develop an appropriate methodology for automatic monitoring of these systems, which, using a minimum set of sensors, makes it possible to predict the state of the vessel and change the dangerous state to the safe one. To implement the method of automatic monitoring, a set of statistical control tools is selected depending on the alleged violations and the level of correlation of parameters. The uncorrelated parameters are monitored by instruments based on the Shewhart map [1], the correlated parameters are monitored on the basis of Hotelling statistics [2]. This approach makes it possible to diagnose the pre-emergency and emergency states of ship control systems in on-line mode. The method used for multi-level integrated monitoring of the technical state of control systems in on-line mode can improve the reliability of identification of the technical state of vessel subsystems and expand the scope of application of monitoring and diagnostics tools. The data obtained can become the basis for the development of rational decisions in the DSS at the level of control subsystems for the vessel transfer from the dangerous to safe state.

1. Introduction

In navigation, great success has been achieved in the development of DSSs; research on a fully autonomous ship, where the ship's control system is able to make decisions and determine required actions, is underway [3]. DSS hardware and software are able to help the navigator make right and timely decisions and automatically manage global safety at ocean crossings. In [4,5], the methodology of intelligent DSS has been proposed. In [6], the tasks of creating systems for automatic, continuous monitoring of all vessel subsystems have been set. This means that monitoring in the DSS with continuous observation, assessment and prediction of the vessel integrity should reflect a continuous sequence of hazardous and safe states at specified time intervals.

2. Problem statement

It becomes clear that monitoring in the DSS should be performed only by automatic systems that completely exclude the human operator. Hence, the task is to develop a methodology for automatic monitoring in the intelligent DSS, which can help predict the state of the vessel and transfer it from the dangerous to safe state with the required reliability.
2.1 Types of monitoring of ship control systems

Monitoring in the DSS can be divided into monitoring of the control and controlled subsystems of the vessel. The article analyzes the system of monitoring of controlled subsystems, which is part of the overall monitoring system of the DSS. Monitoring of the controlled subsystems in the DSS with constant observation, assessment and forecast of the vessel state should reflect a continuous sequence of dangerous and safe states of the internal structure of the ship. The data obtained can become the basis for the development of rational decisions at the level of control subsystems for the transfer of a vessel from the dangerous to safe state.

2.2 Expectation of the functional state of the vessel control system

In accordance with the theory of ship control [7], the controlled subsystem of the ship with a mechanical engine consists of the following parts: a control object (ship's hull) and control facilities: Main control facilities (MCF), Auxiliary control facilities (ACF) and Control steering device (CSD). Depending on the type of a goal set, the following tasks can be distinguished: regulation (course stabilization), situational management (navigation among navigational hazards), planning of an appropriate behavior (prevention of collisions). An indispensable condition for solving these problems is expected results of the controls achieved when changing their operating modes, leading to a change in the speed and course. The output generalized parameters of the ship's controls, indicating their operability, are given in MSC.137 (76) - Standards for the maneuverability of ships [8]. Structurally, the MCF is a propulsion system that includes the main engine, the propulsion unit and the hull. If it is an internal combustion engine, it consists of subsystems for fuel supply, air supply and purification, gas distribution, cylinder-piston group, etc., which form information about their technical and functional state. The generalized output parameter of the engine can be represented by displaying the effective power \( N_{\text{eff.PZH}} \) (if the vessel is loaded \( D_l \) in reverse gear and the stopping distance of the vessel (from "full forward maneuvering speed to full reverse"). This value should be no more than 15L, where \( L \) is the length of the vessel in accordance with MSC.137 (76):

\[
F: N_{\text{eff.PZH}} \times D_l \rightarrow 15L.
\]  

In the event of damage or failure of the control systems, the ship's behavior can become uncontrollable and, it cannot solve the assigned control tasks. The main factors in which the ship becomes uncontrollable are the lack of sufficient thrust force of the engine propeller, the required lateral force when the rudder is deflected, being in an emergency state, etc.

2.3 Indicators of the technical state of the control systems

Output parameters (1) and (2) depend on the technical state of the controls, at which the DSS is able to solve the assigned control problems, determined by the operability and serviceability. To assess the technical condition, indicators such as operational reliability and durability are important. Due to aging or failure of any element, changes in the technical state can occur gradually or abruptly. Deterioration of the internal characteristics, which decrease the efficiency of the executive bodies lead to a decrease in the quality when solving control problems. Uncompensated deviations from the required movement create a threat to the desired result.
2.4 Functional roughness of the MPPCS-72 algorithms [9] in determining the technical state of ship control systems.

In practice, the ship's controls can be in one of three states: "serviceable and functional", "malfunctioning, but functional" and "malfunctioning and inoperative". In the court case on the collision of "Glamorgan" - "Caland" in 1893, Lord Chancellor Harshall said:" the likelihood of a machine stopping due to its incomplete serviceability is not a basis for recognizing the vessel as being deprived of the ability to control "[10]. This principle of dividing ships into controlled and uncontrolled is reflected in COLREGs-72. "Ship management in a pre-emergency state":any "power-driven vessel" is always controllable; under paragraph (f), "uncontrollable vessel" means a vessel that, due to some exceptional circumstances, is unable to maneuver as required by these Rules, and therefore cannot give way to another vessel. Other classifications of ships by their ability to maneuver have certain restrictions associated with the nature of activities performed, i.e. the functional (controlled) state of the controls is good. Thus, the MPPSS-72 provides a rough gradation of the technical state of the controls. To take action, the navigator needs to solve the problem of "additional degrees of freedom" ("stay away", "until the latter is finally passed and left behind", etc.) in order to achieve the required level of safety. Such coarseness of the COLREG-72 algorithms complicates the linking of the technical state of the ship controls and actions provided for by the MPPSS-72 when constructing DSS algorithms.

2.5 Tasks of automatic monitoring of ship control systems.

DSS and the fully autonomous ship will need a clear picture of the functional state of the internal structure of the ship and a possibility of diagnosing the nodes and mechanisms of control means in order to predict the state of the ship, the quality of its control and its maneuverability by formulas (1) and (2). The effective monitoring requires a system analysis of control tools in order to identify and typify degradation processes of the technical state of the most loaded and critical units and parts that limit the reliability and durability of equipment, to determine the rational depth of diagnosis, to systematize diagnostic tasks, to choose diagnostics methods, and to determine the initial prerequisites for research and development of fundamentally new diagnostic techniques.

3. The method of multilevel integrated control of the technical state of the ship's controls. The method is based on the assessment of the technical state of the controls, which is carried out by the measurements of parameters using a set of sensors at regular intervals, which form a system of interconnected time series. For this system, a mathematical model which predicts changes in its characteristics and detects violations before the controlled parameters go beyond the limit values has been built.

3.1 Statistical tools for controlling uncorrelated parameters.

Monitoring has a classical meaning of "tracking" the technical parameters ($x_1$, $x_2$, ..., $x_n$). Deterioration of the output characteristics, which are the reason for the decrease in the effectiveness of the management of controls, creates a threat to the desired result. The controls ($S_{mn}$) can have three states: normal (nominal) ($S_n$), emergency ($S_e$) and catastrophic ($S_k$). Taking into account different modes, the entire state space $S_m$ can be written as a union of subspaces:

$$S_m = S_n \cup S_e \cup S_k,$$

and, accordingly, a set of variables ($X_{mn}$) describing $S_m$:

$$X_{mn} = \{x_{n1}, \ldots, x_{n-1}, x_n, x_{a1}, \ldots, x_{a-1}, x_a\}.$$

Depict the processes that can occur in $S_m$ in Figure 1. Along the ordinate, postpone the values of threshold parameters $X_{mn}$ of the variable $x_i$ of the internal state of $S_m$. The ship's controls are a dynamic
system operating in time (T); therefore, plot the current time $t$ along the abscissa axis. Symbols $x_i^{ln}$ and $x_i^{un}$ denote the lower and upper boundaries of the normal functioning mode $S_n$, and $x_i^{an} x_i^{av}$ - the critically dangerous lower and upper boundaries of the transition from the emergency $S_e$ to catastrophic $S_c$ state. As a result of the emergence of emergency parameter values on the interval $\Delta t = t_2 - t_1$, a smooth or stepwise degradation of $S_n$ is possible; it reduces the efficiency of the controls, and at $t > t_2$, the final destruction of the control structure occurs. The graph in Figure 1 is similar to Shewhart's maps or control charts, which are used to analyze the statistical controllability of controls. The control charts characterize the parameters of a process in order to identify and eliminate causes of special variability, which should ensure the safe state of the ship's controls.

In stationary mode, the state of the controls is often considered abnormal if the stability of the control process is disturbed. Shewhart’s control charts can be used to control independent parameters of the ship's control process [1]. However, the monitoring and control of complex multi-parameter systems can be controlled by many subsystems (Figure 2). Thus, we are talking about the diagnosis of a multi-parameter process with many correlated parameters.
3.2 Statistical tools to control correlated parameters.
To develop a methodology for assessing the stability of the controls, a preliminary analysis of the monitoring results is carried out under normal conditions (bench or running tests). At the same time, the level of correlation of indicators is determined (taking into account their significance); they are divided into groups of independent and correlated [11,12] ones. Statistical tools are selected for control: for independent indicators, standard Shewhart’s maps are used [1], for the correlated ones - methods and algorithms based on the multivariate Hotelling statistics and generalized variance [13, 14].

3.3 Assessment of the stability of independent indicators.
To control the stability of uncorrelated indicators, Shewhart’s maps can be used [13, 14]. On the map of average values, the average value of the controlled indicator $X$ in the $t$-th sample is plotted ($t = 1, ..., m$, $m$ is the number of samples):

$$
\overline{x}_t = \frac{1}{n} \sum_{i=1}^{n} x_{ti},
$$

($x_{ti}$ is the result of the $i$-th observation in the $t$-th instant sample of volume $n$), which is plotted. The position of the center line is determined by formula:

$$
\bar{x} = \frac{1}{m} \sum_{t=1}^{m} \sum_{i=1}^{n} x_{ti}.
$$

To estimate the scatter, the unbiased variance of each instantaneous sample is calculated:
The position of the control boundaries of the average map is determined by formulas:

\[ \text{UCL} = x + A_3 \bar{s}, \]
\[ \text{LCL} = x - A_3 \bar{s}, \]  
where \( A_3 \) is the coefficient determined from Table [1] depending on the sample size \( n \).

On the map of standard deviations, the values of the square root of variances (7) are plotted, the center line is determined by formula (8), and the position of the control boundary is determined as

\[ \text{UCL} = B_4 \bar{s}, \]

where \( B_4 \) and \( A_3 \) are the tabular coefficients.

### 3.4 Assessment of the stability of a group of correlated indicators.

Ship controls are multidimensional subsystems. In practice, the processes of movement and course changes are characterized by a set of indicators that have a joint normal distribution correlated with each other. The state of the subsystems is assessed by the method of disaggregating each of the subsystems, based on the statistical analysis of the measured parameters of the elements. During bench tests, a "reference profile" is created. It is stored as matrices of technical states. The subsystem is diagnosed under favorable environmental conditions, when they do not affect the instantaneous values of psensors. The measurement results are stored in the form of vectors, and the \( N \times N \) matrix of the actual functional state of the subsystem is formed and compared with the readings of the reference profile. Taking into account the rate of exit of the controlled parameter outside the confidence range, the level of the pre-emergency state of the controlled element is determined.

To control \( u \)-indicators having a joint normal distribution, to control the average level of the multidimensional process, the Hotelling algorithm is used [2, 14]: for each \( t \)-th instantaneous sample (\( t = 1, ..., m \)), the statistics is calculated:

\[ T_t^2 = u(x_t - \mu_0)^T S^{-1} (x_t - \mu_0) \]  
where \( u \) is the instantaneous sample size, \( x_t \) is the vector of means in instantaneous samples, \( \mu_0 \) is the vector of the target means, \( S \) is the covariance matrix estimate \( \Sigma \).

The estimates for the components of the covariance matrix \( S \) are determined by formula:

\[ S_{jk} = \frac{1}{m(n-1)} \sum_{t=1}^{m} \sum_{i=1}^{n} (x_{ijt} - \mu_j)(x_{ikt} - \mu_k), j, k = 1, ..., p. \]  

The process is considered to be stable when \( T_t^2 < T_{kp}^2 \), where

\[ T_{kp}^2 = \frac{j(m-1)(\mu - 1)}{mu - m - j + 1} F_{1-a}(j, mu - m - j + 1), \]  
where \( F_{1-a}(k_1, k_2) \) is the quantile of the Fisher distribution with numbers of degrees of freedom \( k_1 \) in the numerator, \( k_2 \) in the denominator; \( a \) – false alarm probability.

If the covariance matrix \( \Sigma \) is known, the Hotelling statistic has \( \chi^2 \) distribution; in this case, the control boundary is equal to
The process is statistically controllable if $T_{k_p}^2 < T_{k_p}^2$.

Let $T_0, T_0^2 > T_{k_p}^2$. The violation of the technological process is recorded on the map; the Hotelling map does not show which of the quality indicators causes the violation. The question about the interpretation of the control results arises. To test the hypothesis, the Hotelling criterion can be used [15]. The hypothesis is correct if

$$T_j^2 = \frac{n\left(c_j^T (X_{te} - \mu_0)\right)^2}{c_j^T S c_j} > T_{k_p}^2,$$

where $c_j$ - the column vector consisting of zeros in all rows except the $j$-th row and ones in the $j$-th row.

If all hypotheses are rejected, the violation of the process is caused by the joint effect of several indicators. To test the hypotheses about the joint effect of two indicators, the $c_j$ column is corrected: in the corresponding two rows, zeros are replaced by ones. Thus, using the particular Hotelling criterion, it is possible to identify the reason for the violation of the technological process.

3.5 Program for detecting violations of the ship control process.

The program (Figure 3) is designed to diagnose violations during the multidimensional statistical control of ship controls.

**Figure 3. Vessel control violation detection program**

Initial data include the number of parameters, the number of observations in the sample, the number of samples, and the measurement results. Depending on the degree of correlation, the parameters can be combined into groups, and maps for each group can be built. The program includes two subsystems: for detecting structures on the Hotelling map; for building a map with a warning...
border with a search for a sequence of points located between the warning and control borders. The program tests the control process by identifying violations. At the same time, to diagnose possible violations of the ship control process, the maps with a warning boundary [16] and the Hotelling maps [17, 18, 19] can be used.

4. Conclusion
The tools for monitoring the ship's control system allow for multi-level complex monitoring of the technical state of the ship's controls, taking into account classes of the technical state. The methodology for assessing their stability involves the following stages:

1) during bench tests, a "reference profile" is created; it is stored as matrices of the technical state and possible violations are revealed;
2) in favorable conditions, readings of the sensors are taken and the main statistical characteristics are calculated: vectors of mean values and covariance matrices;
3) a set of possible statistical tools is selected for subsequent control, depending on the alleged violations and the level of correlation of parameters. The uncorrelated parameters are controlled by the tools based on the Shewhart’s map, the correlated ones are controlled by the Hotelling statistics;
4) constant monitoring of the system is performed in order to diagnose stability disorders;
5) the obtained data become the basis for the development of rational decisions in the DSS at the level of control subsystems for transferring the ship from the dangerous to safe state;
6) to diagnose possible violations in the ship control process, maps with a warning boundary and Hotelling maps can be used.

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