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METHODOLOGY OF DESIGNING SYSTEMS FOR SPATIAL STABILIZATION

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Abstract*—This article presents a study of the design features of spatial stabilization systems. The described methodology covers basic methods and procedures necessary for the creation of a precision, resistant to disturbances, and at the same time controllable system for precision stabilization of the equipment assigned for operation on moving vehicles of a wide class. The block diagram explaining the interconnection between basic methods and procedures for designing spatial stabilization systems is represented. The algorithms for choosing the controllable system structure and the synthesis of the robust controller are described. The procedures for the choice of the system's components and modelling of both system components and the system as a whole are presented. The features of the modern approach to data processing based on neural networks are described. The obtained results can be useful for the spatial stabilizing objects assigned for operation on moving objects of a wide class.*

Keywords—Spatial stabilization; controllable structure; robust controller; modelling; design methodology.

I. INTRODUCTION AND PROBLEM STATEMENT

Solving the problems of spatial stabilization of mobile objects' equipment is possible on the basis of modern, scientifically based approaches [1] – [3]. At the same time, it should be emphasized that improving the characteristics of information and measuring devices that are part of the equipment of mobile objects may not give the expected effect without ensuring high-precision stabilization of the moving base of their installation. An additional complication is that the functioning of the specified information and measuring devices occurs in conditions of movement and is accompanied by the influence of significant external disturbances. The main goal of the research is to create a system capable of maintaining high accuracy under disturbances and of being adaptable to checks. In particular, during the operation of aircraft equipment, aerodynamic disturbances occur.

II. DESCRIPTION OF METHODOLOGY

The methodology for designing a robust spatial stabilization system with a high level of controllability includes a set of methods and procedures, such as:

1) the procedure for determining the requirements for the stabilization system;

2) the procedure for selecting the components of the stabilization system;

3) the procedure for modeling the components of the stabilization system;

4) the method for synthesizing the structure of the controllable stabilization system;

5) the procedure for determining the permissible parameters of the system;

6) the method of modified robust parametric synthesis of the stabilization system;

7) the procedure for processing information based on adaptive filtering;

8) the procedure for modeling the synthesized system.

The relationship of these methods and procedures is shown in Fig. 1.

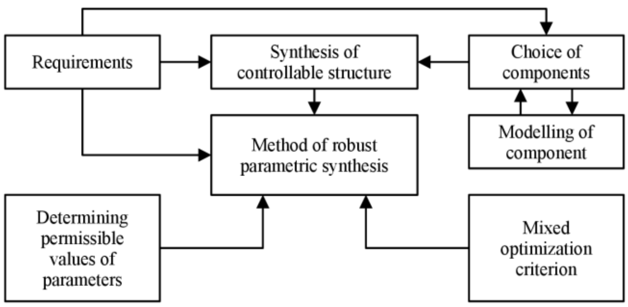

Fig. 1. Interconnection between the methods and procedures of designing spatial stabilization systems: P is a procedure; M is a method

The proposed methodology includes two methods, namely: the method of synthesizing the structure of a controllable stabilization system and the method of modified robust parametric synthesis.

The method of synthesizing the structure of a spatial stabilization system based on a generalized controllability index contains such stages [4].

1) Formalized description of the structure of the spatial stabilization system based on graph theory [5] and determination of rules for transforming the structure by automated means.

2) Determination of a generalized multiplicative quality indicator of controllability based on the most significant controllability indicators (completeness of control, depth of defect search, etc.) and weight coefficients that determine the importance of each indicator. Weight coefficients were determined based on expert assessments, namely the method of prioritization.

3) Setting permissible restrictions based on the specifics of the developed system (weight and dimensions, accuracy, reliability).

4) Solving the optimization problem based on gradient methods. The goal of optimization is to achieve the maximum value of the generalized controllability indicator of the system, provided that the specified constraints are met.

5) Verification of the obtained results.

The block diagram of this algorithm is represented in Fig. 2.

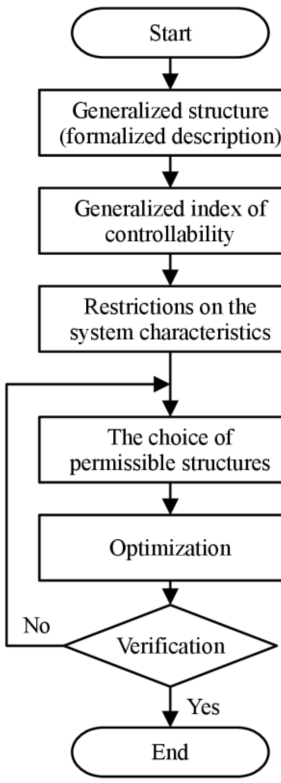

Fig. 2. The algorithm for the synthesis of a controllable system

When implementing the method of synthesis of the structure of the controllable system, variants of possible structures of the stabilization system are formed based on the tasks set and the procedures for determining requirements and selecting components. If necessary, the process of selecting system components is supplemented by the procedure for modeling system components. The determination of structure variants is carried out on the basis of redundant information about possible implementations of the measuring system and the executive drive. Based on a rather limited number of such possible variants, the gradient search method is used to implement the actual optimization procedure.

Next, the most important indicators of the system's controllability are calculated, which include the completeness coefficient of the controllability check, the failure search depth coefficient, the redundancy coefficient, and the unification coefficient of the coupling devices. For a more accurate representation of the generalized controllability indicator, weight coefficients were calculated, which are determined by ranking the controllability indicators by importance. For this purpose, a survey of experts was conducted and a table of comparative assessments was compiled. Then, a well-known method of prioritization was used and weight coefficients were calculated. Based on the prepared data, a generalized multiplicative controllability indicator was determined, since each of the controllability indicators is less than one. Among the obtained structure options, systems with the highest level of controllability are selected. The procedure for determining permissible parameters is the logical conclusion of the method of synthesizing the structure of a controllable system.

The method of the synthesis of control system is based on a mixed robust parametric optimization of the H_2/H_∞ type and differs from existing approaches by using an additional penalty function [6], [7]. This function is formed on the basis of monitoring key performance indicators of the corresponding class of systems, in particular, tracking error, stabilization error, error caused by disturbances, and angular stiffness. It should be emphasized that angular stiffness is one of the most important quality criteria for spatial stabilization systems used on ground-based mobile objects. The introduction of an additional penalty function made it possible to evaluate the quality indicators of the stabilization system directly during the synthesis process, and not after its completion, which generally contributes to reducing the duration of the optimization procedure [6].

The block diagram of the algorithm is shown in Fig. 3.

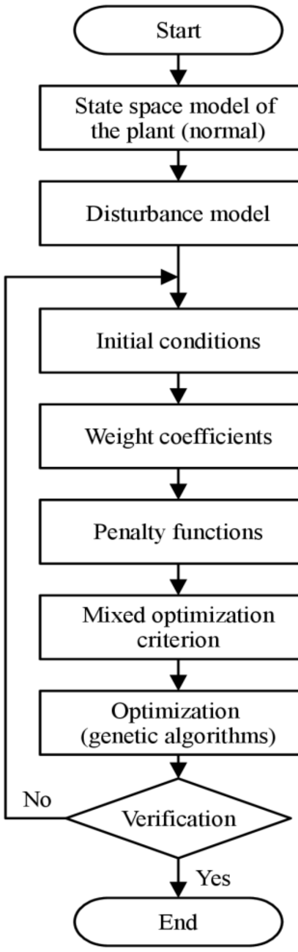

Fig. 3 The algorithm of the synthesis of the robust controller

The implementation of the specified method requires the use of a set of mathematical descriptions. These include system models taking into account nonlinear properties characteristic of real objects, as well as mathematical representations in the state space.

The presence of such descriptions makes it possible to determine the transfer functions of the system and form the sensitivity function and its complementary sensitivity function. The method of robust parametric optimization by H_2/H_∞ norms is based on the use of H_2- and $H\infty$-norms of the specified functions [8], [9].

To increase the efficiency of the optimization process, H_2-norms of sensitivity functions in both deterministic and perturbed modes were introduced into the combined quality indicator.

The implementation of this approach requires the use of forming filters, the structure of which is determined by the type of moving object and the nature of the disturbances. In particular, Dryden filters are used for aircraft, for marine moving objects – forming filters based on the spectral densities of irregular sea waves, and for land moving objects – filters based on the spectral densities of disturbances caused by the relief and terrain features.

It should be emphasized that the formation of mathematical models of spatial stabilization systems should be carried out using MATLAB application programs, in particular Control System Toolbox (CST), Robust Control Toolbox (RCT), and Simulink [10] – [13]. The use of mathematical models in different phases of designing spatial stabilization systems is represented in Fig. 4.

The essence of mixed robust parametric optimization is to minimize the integral quality indicator formed on the basis of the relevant norms. Solving this problem involves the need to find a balance between accuracy and robustness. Achieving such a balance is ensured by introducing weighting factors to the combined criterion of mixed parametric optimization. Changing the values of these factors allows you to adjust the contribution of accuracy and robustness to the generalized indicator "quality-robustness".

An important stage in the proposed set of methods and procedures for designing spatial stabilization systems for moving object equipment is the modelling of the synthesized system.

This stage is implemented in the MATLAB environment and involves performing tests using both linear and nonlinear mathematical models of the system.

The most effective means of conducting research based on nonlinear models is the Simulink application package. A characteristic feature of the modelling procedure for systems of this class is to ensure the maximum possible approximation of the results obtained using mathematical models to the experimental test data [14], [15].

The final stage is improved processing of angular velocity sensor signals by implementing adaptation based on a non-recursive filter, which ensures increased stabilization accuracy in operating conditions.

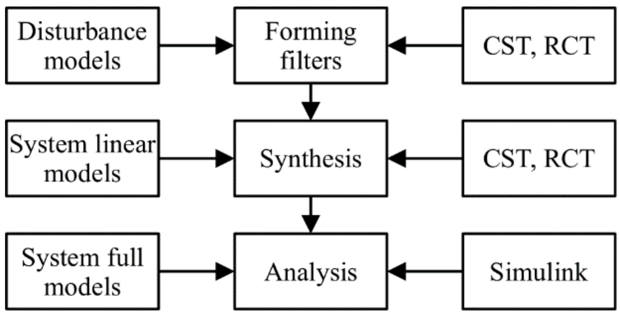

Fig. 4. The use of mathematical models in the design process

III. GROUNDING REQUIREMENTS AND CHOICE OF COMPONENTS

The choice of the structure of the spatial stabilization system is determined by its functional purpose, the type of moving object, accuracy requirements, mass and dimensions, resistance to external disturbances and a number of other factors, in particular controllability. In this case, it is advisable to take into account the criterion of "efficiency–cost".

The numerical values of the main operational parameters are substantiated, taking into account the tolerances and dynamic influences acting on the spatial stabilization system during its operation, namely [1]:

- minimum and maximum platform rotation speeds along all axes;
- the limiting value of the platform angular acceleration in the stabilization contour;
- static and dynamic accuracy of the tracking and stabilization contours. The choice of the structure of the spatial stabilization system is determined by its functional purpose, the type of moving object, accuracy requirements, mass and dimensions, resistance to external disturbances and a number of other factors, in particular controllability. In this case, it is advisable to take into account the criterion of "efficiency–cost".

One of the key stages of designing a stabilization system is the selection of basic components that meet the specified requirements. Such components include:

- angular velocity sensors that provide the necessary accuracy and performance under vibration and shock loads;
- angle sensors with similar requirements for accuracy and operating conditions;
- electric motors mounted on the gimbal frame of the platform, with the determination of their main parameters: nominal and starting torques, power, as well as maximum and minimum rotation speeds;
- electronic components, including amplifiers, pulse-width modulators, filters, power supplies and other devices.

Let us consider the features of choosing key parameters for individual elements of the spatial stabilization system of equipment used on moving objects.

In this system, the stabilization object is a platform on which equipment for various purposes is placed. The defining parameters of this object, which directly affect the selection of other components of the system, are the moments of inertia of the platform relative to the corresponding axes. An important role is also played by the estimates of disturbing moments that may arise during operation. In this case, it is necessary to take into account three main groups of influences: friction moments in the suspension supports, moments due to imbalance, as well as moments arising from the angular movement of the carrier object under the influence of external disturbances. Such disturbances include aerodynamic effects, regular and irregular oscillations, unevenness of the road surface or terrain - depending on the type of aircraft, sea or land moving objects. Important initial information for assessing these parameters is the characteristics of the payload.

When choosing angular velocity sensors, it is advisable to focus on modern inertial technologies. Laser and fiber-optic gyroscopes are appropriate for systems with small and medium mass-dimensional indicators. However, for equipment with significant mass-dimensional characteristics and in operating conditions accompanied by strong shocks and other mechanical influences, microelectromechanical (MEMS) and Coriolis vibration gyroscopes are promising. As a rule, such conditions are typical for spatial stabilization systems of equipment of ground moving objects.

After determining the type of inertial technology, we proceed to the selection of the main characteristics of angular velocity sensors used in stabilization and tracking circuits.

When choosing an angular velocity sensor, one should take into account the conditions of its actual operation, primarily shock resistance. The next stage is the analysis of errors, in particular temperature errors, which affect the provision of high accuracy of the angular velocity sensor during use. Special attention should be paid to the error of setting the angular velocity sensor, since for MEMS gyroscopes in some cases it is quite significant, which can reduce the effectiveness of measures aimed at increasing the accuracy of angular velocity measurement.

When choosing the type of engine, it is necessary to take into account the mass of the payload and, accordingly, the dimensions of the platform. With significant platform dimensions and a large payload, it is advisable to use actuators based on a motor with a gearbox. In spatial stabilization systems for moving object equipment, preference is given to DC motors, which are characterized by high linear control and mechanical properties. If the mass and dimensions of the platform are insignificant, then it is advisable to use gearless drives to create high-precision stabilization systems. In such systems, torque-free contactless motors are usually used, when choosing which it is important to correctly determine the permissible torque on the shaft taking into account the working load.

IV. Mathematical Modelling

The essence of this procedure is to build mathematical models of individual components of the spatial stabilization system, in particular angular velocity sensors, actuators, etc. Next, a generalized mathematical model of the control object is formed, which includes the measuring system and the actuator, after which its modelling is carried out in order to determine the dynamic characteristics. Based on the obtained modelling results, it is possible to make changes to the mechanical design of the spatial stabilization system, in particular by increasing or decreasing the rigidity of its elements. Mathematical models of sensors and actuators taking into account the payload (equipment of moving objects) should be developed using the extended Simulink package of the MATLAB computing environment, since such models are the most visual and convenient for the designer.

When building a mathematical model of the angular velocity sensor, special attention should be paid to the mathematical description of random errors. An example of such a model based on the ADIS16488 MEMS gyroscope and its logarithmic amplitude characteristics are shown in Figs 5 and 6.

An important component of the spatial stabilization system is the drive.

As a rule, the drive model of the spatial stabilization system is developed taking into account the payload (equipment on ground-moving objects) and the effects of setting and disturbing influences.

The drive model of the spatial stabilization system for ground-moving objects, implemented in Simulink, is shown in Fig. 7.

The transfer function with respect to the control disturbance is given in the following form [1].

$$W_{drive} = \frac{\omega(s)}{U(s)} = \frac{c_m}{L(J_{frm} + J_{mot})p^2 + [R(J_{frm} + J_{mot}) + Lf_m]p + Rf_m + c_m c_e}, \qquad (1)$$

where J_{frm} is the moment of the frame inertia; J_{mot} is the moment of the motor inertia; c_m is the coefficient of the proportionality between the current of the armature circuit and loading at the motor shaft; c_e is the counter electromotive force coefficient; L, R are the inductance and resistance of motor armature windings; f_m is the coefficient of the harmonic linearization for dry friction forces.

The approximating coefficient of viscous friction is defined as the ratio of the amplitude of the first harmonic of the friction torque to the amplitude of the velocity.

$$f_m = 4M_{nom} / (\pi\Omega), \qquad (2)$$

where M_{nom} is the nominal moment; Ω is the motor rate.

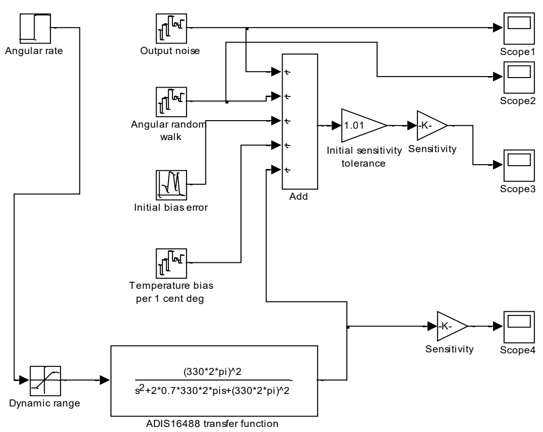

Fig. 5. The mathematical model of angular rate sensor

When modelling the drive, it is necessary to take into account both constant disturbing influences, given in the form of a step signal, and random influences, caused, in particular, by unevenness of the road surface and terrain during the movement of a ground object with installed equipment.

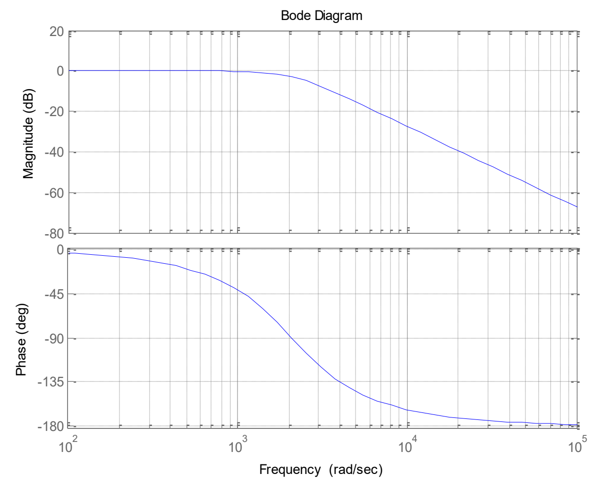

Fig. 6. Logarithmic amplitude frequency characteristics

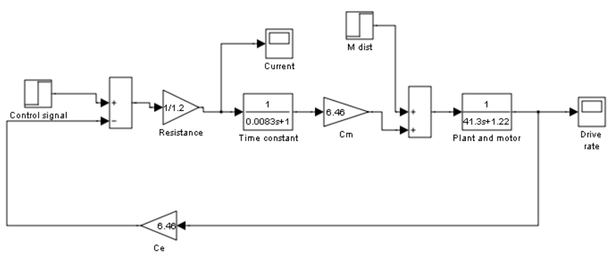

Fig. 7. Simulink model of the drive model with a payload

Such random disturbances are modelled by applying white noise to forming filters that correspond to the spectral densities of unevenness of roads and terrain of various types. It is also advisable to model sinusoidal motion, which corresponds to the profile of the test track. The logarithmic amplitude-frequency characteristics of the drive with a payload are shown in Fig. 8.

The purpose of this stage is to simulate closed loops of the synthesized spatial stabilization system using the MATLAB Control System, Robust Control and Simulink Toolboxes. In the Simulink package, the simulation is carried out taking into account all possible nonlinearities and specific features that could not be taken into account at the synthesis stage, in particular, elastic deformations, the influence of misalignments, imbalances, etc.

In the process of research, the behavior of the system under the action of external and internal disturbances of various natures that arise during operation is analyzed. This stage is defined as Model-in-the-Loop Simulation, i.e. simulation with a model of the control object in a closed loop.

Based on the simulation results, the dynamic and static indicators of the system and their compliance with the established technical requirements are evaluated. If necessary, additional correction of the system parameters and control laws is carried out. At the final stage, the final selection of the discreteness interval of digital regulators and the modelling of the system with digital control are performed with possible refinement of the parameters based on the obtained results.

For systems of this type, it should be taken into account that real operating conditions are accompanied by the action of shock loads. In this regard, after analyzing the characteristics of possible shock effects, it is necessary to perform additional modelling with simulation of their action. The final value of the sampling frequency is determined based on the results of such modelling in order to ensure the stability of the system under shock effects.

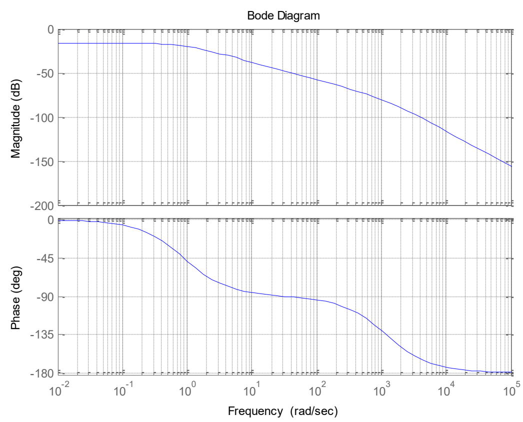

Fig. 8. Logarithmic amplitude-frequency characteristics

The assessment of the main characteristics of the system is carried out as follows. The static accuracy of the stabilization system is determined in steady-state modes at constant values of the command signals. In the general case, studies are carried out both in tracking modes (provided that the angular velocity is set) and in stabilization modes (when the set angular velocity is zero, and the angular velocity of the object on which the platform is located is considered as a disturbing effect). The analysis of the dynamic properties of the system is performed based on the assessment of the quality of transient processes, taking into account such indicators as speed, overshoot, and level of oscillation.

The accuracy of the spatial stabilization system, can be estimated by errors in different typical modes. The stabilization error is determined by modelling the angular motion of the carrier object. The dynamic error is estimated for the motion by the harmonic law (Fig. 9). For ground-moving objects, this law corresponds to the movement along a certain test track.

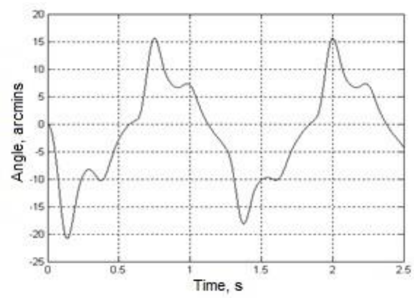

Fig. 9. The harmonic error

V. Features of Data Processing

The key prerequisite for the effective use of angular velocity sensors is the creation of algorithms for digital processing, in particular filtering procedures. In real-time signal filtering tasks, it is advisable to give preference to filters with minimal phase delay. Achieving zero phase delay is possible by using centered filters with a symmetric amplitude-phase characteristic, however, such filters are physically unrealizable due to the need to process future values of the input signal. The synthesis of a physically realized filter with zero phase delay is impossible, however, provided that there are statistical dependencies between the signal components, it is possible to use methods for predicting its future state (Kalman filter).

To develop such filters, it is necessary to have information about the statistical mathematical model of the signal and a given bandwidth. In real operating conditions, the statistical characteristics of the signal can change significantly depending on the operating modes and over time. In this regard, the task of developing a practical approach to approximating physically unrealized filters with a finite impulse response, taking into account the real statistical properties of the filtered signal, arises. The most promising tool for solving this problem is the use of neural networks. Figure 10 illustrates a flowchart of the filtering process implemented using time-delay neural networks.

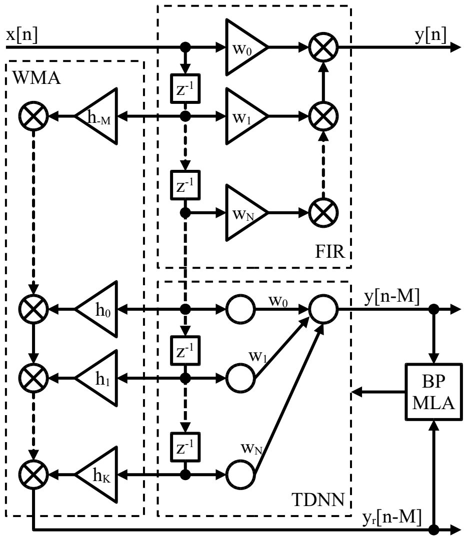

Fig. 10. The flowchart of the adaptive filtration based on a neural network with a time delay

VI. Conclusions

The methodology of designing systems for spatial orientation, consisting of two methods and five procedures, is represented. The block diagram illustrating the interconnection between the above-stated methods and procedures is represented. The characteristics of the method for the synthesis of the controllable system structure and the synthesis of the robust controller are described. The brief representation of design procedures is given. The block diagrams of algorithms and simulation results characterize the features of the proposed methodology.

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Ю. В. Мельник, О. О. Салюк. Методологія проєктування систем просторової стабілізації

У цій статті представлено дослідження особливостей проєктування систем просторової стабілізації. Описана методологія охоплює основні методи та процедури, необхідні для створення точної, стійкої до збурень та водночас контролепридатної системи для точної стабілізації обладнання, призначеного для роботи на рухомих об'єктах широкого класу. Представлено блок-схему, що пояснює взаємозв'язок між основними методами та процедурами проєктування систем просторової стабілізації. Описано алгоритми вибору структури контролепридатної системи та синтезу робастного регулятора. Представлено процедури вибору компонентів системи та моделювання як компонентів системи, так і системи в цілому. Описано особливості сучасного підходу до обробки даних на основі нейронних мереж. Отримані результати можуть бути корисними для об'єктів просторової стабілізації, призначених для роботи на рухомих об'єктах широкого класу.

Ключові слова: просторова стабілізація; контролепридатна структура; робастний регулятор; моделювання; методологія проєктування.

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