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[1]**Olha Sushchenko,**
[2]**Mykola Dyvnych**

DESIGNING TWO-AXIS GIMBALED CONTROL SYSTEMS FOR OBSERVATION UNITS STABILIZATION

Faculty of Air Navigation, Electronics and Telecommunications, State University "Kyiv Aviation Institute," Kyiv, Ukraine
E-mails: [1]sushoa@ukr.net ORCID 0000-0002-8837-1521,
[2]npdvn@gmail.com ORCID 0009-0000-6260-0069

Abstract—*This article presents features of designing a two-axis inertially stabilized platform assigned for stabilization of observation units and devices, for example, cameras. The problem of stabilization of images is analysed, including electromechanical, optical, mechanical, and computer techniques. The appropriate structural diagrams are represented. The procedure of the synthesis for the inner and outer tracking loops of the control system is represented. The structure of control laws is proposed. The combined optimization criteria that ensure compromise between the tracking accuracy and resistance to disturbances on angular rate are represented. The structures of the synthesised regulators are described. The results of the synthesized system simulation are shown. The analysis of the simulation results is given. The system's norms are calculated. The obtained results can be used in the area of stabilization of a wide class of instrumentation assigned for operation on moving objects.*

Keywords—Two-axis gimbals, stabilization, tracking system, regulator, simulation, design approach.

I. INTRODUCTION

The current problems of ensuring high accuracy of stabilization and tracking processes for a wide class of information and measuring devices operated on moving objects can be solved on the basis of inertial stabilization principles. Among the scientific and commercial applications that require the use of inertial stabilization principles, air and sea navigation, communications, and surveillance can be distinguished. Maintaining a constant orientation of information and measuring devices in the direction of the observation object becomes a difficult task if the information and measuring devices are installed on a moving object. Controlling the orientation of information and measuring devices using inertial stabilization principles enables the solution of this difficult problem. The principles of inertial stabilization are used for stabilization and direction determination in communication antennas and laser devices. The most recent application of inertial stabilization is the stabilization of mobile satellite communication antennas.

II. PROBLEM STATEMENT

Using the specified approach, stabilization of conventional and infrared cameras, as well as surveillance equipment of various types, installed on land, water, aircraft, and space-based platforms, can be carried out, allowing various tasks, for example, imaging the environment.

The problem statement is as follows. The typical kinematic diagram of the observation equipment in double gimbals is represented in Fig. 1.

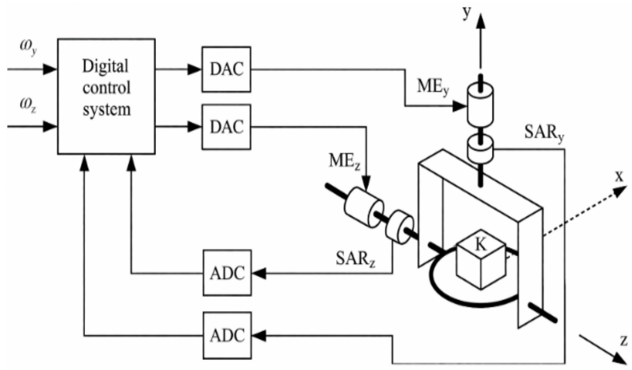

Fig. 1. The observation equipment in double gimbals: DAC is a digital analog converter; ADC is an analog digital converter; ME is a moment electromotor; SAR is a sensor of angular rates; C is a camera (observation device)

It is necessary to determine approaches to the representation of images and propose procedure for the synthesis of both control loops of the gimbaled payload. Only solution of both tasks can lead to the creation of the system able to ensure the precise stabilization of the observation equipment. The main goal of the article is to propose approaches to image stabilization and carry out the robust synthesis of a servo system for stabilizing observation equipment mounted on a controlled platform in two-axis gimbals.

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III. APPROACHES TO IMAGE STABILIZATION

Electromechanical image stabilization is implemented by using a double gimbal, consisting of an external (coarse) and internal (fine) contours. The external gimbal is part of the information-stabilizing platform and is installed on its base, while the internal gimbal serves to accommodate the observation equipment [1], [2]. The kinematic structure of the azimuth axis of this gimbal is shown in Fig. 2. In this case, the internal gimbal is kinematically isolated from the base platform, which allows for increasing the efficiency of stabilization of the surveillance camera.

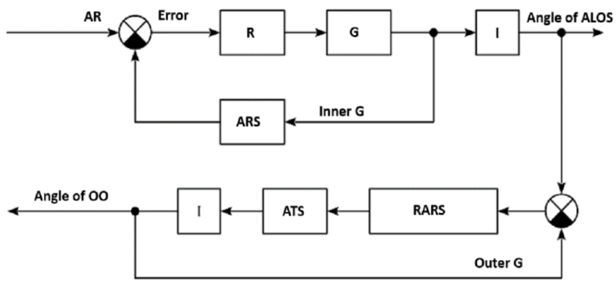

Fig. 2. Generalized structural diagram of the electromechanical image stabilization: AR is angular rate; R is regulator; G is gimbals (including the actuator and amplifier); I is integrator; LOS is line of sight; ARS is angular rate sensor; OO is observation object; ATS is automatic tracking system; RARS is relative angular rate sensor

As shown in Fig. 2, the closed loop of the internal gimbal with angular velocity feedback is similar to the internal stabilization loop of the information-stabilizing platform. It is worth emphasizing that the angular velocity sensor can be installed on both the internal and external gimbal. If it is placed on the external gimbal, its signal can be used both in the external loop (as a derivative of the angle of rotation of the external frame) and in the internal loop (as a quantity proportional to the disturbance affecting it).

The image stabilization system shown in Fig. 2 not only protects the internal loop from external disturbances, but also significantly reduces the impact of internal disturbances that arise during the movement of the gimbal and manifest themselves as additional moments of interaction between its frames. In addition, this system allows you to scan the terrain to detect the object of observation in both manual and automatic modes.

The optical-mechanical method of image stabilization is based on the use of a mirror system, which includes a stabilized mirror and a mirror with a controlled angular position, which is regulated by a high-speed tracking system. The image of the observation object first falls on the stabilized mirror, placed on the external (coarse) gimbal, after which it is reflected and, through the optical system of lenses, is directed to the high-speed controlled reflector, installed in a compact separate gimbal. The control system quickly changes the position of this mirror in such a way as to compensate for high-frequency oscillations caused by the disturbed movement of the aircraft [3], [4]. The gyroscope of the outer contour and the stabilized sensor, which includes a stabilized mirror and a lens system, are rigidly fixed on the external gimbal. The image formed by this sensor is fed to the high-speed controlled reflector, which provides image stabilization, and therefore, the lines of sight. Figure 3 shows a block diagram of an information-stabilizing platform with an optical-mechanical image stabilization system. The input of this circuit is a command signal of angular velocity, which is formed by the operator or an automatic system for tracking the object. The deviation in angular velocity is integrated, resulting in an error in the angle of rotation, which is fed to the closed loop of the image motion compensation mechanism. It is this mechanism in this system that provides image stabilization.

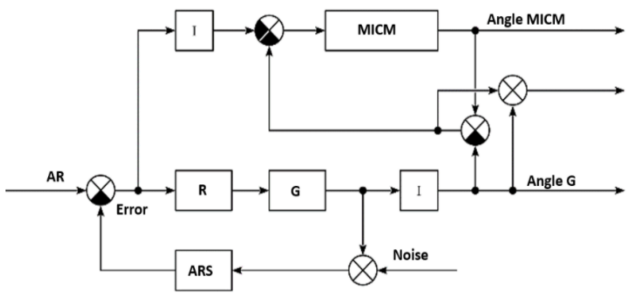

Fig. 3. Structural diagram of the inertially stabilized platform with optical-mechanical image stabilization: MICM is moving image compensation mechanism

The rotation angle of the compensation mechanism (the fast-controlled mirror) is actually the angular error of the stabilization circuit of the external gimbal. This error is subtracted from the rotation angle of the external control loop, as a result of which the angular position of the line of sight is formed. It is worth noting that in this way not only broadband external disturbances are compensated, but also gyroscope noise. Since the mass of the moving mirror is much smaller than the mass of the surveillance camera, the bandwidth of the internal circuit in this system is significantly larger compared to systems with electromechanical image stabilization. This provides higher-quality image stabilization.

The computer approach to image stabilization is based on achievements in the field of digital processing. The intensive development of these methods has made it possible to create stabilization systems without the use of additional electromechanical devices, such as a gimbal. Modern processing algorithms have high speed, which allows stabilization to be performed in real time [3]. They are based on mathematical methods, including extended Kalman filtering, contrast enhancement using two-dimensional fast Fourier transform, image compression, and other approaches.

Compensation of the motion of the observation object in the field of sight of the observation camera is carried out by frame-by-frame processing of line-of-sight images with a small time interval of sampling. At each moment, the image displacement relative to the camera center is determined, and the discrepancy in the horizontal and vertical planes is calculated, which is then used by the automatic system for tracking the external contour of the image.

High-frequency components of the image motion are suppressed by modern optimal filtering algorithms. Due to the wide range of image processing algorithms, it is possible to create different types of such systems.

The choice of a specific mathematical support for a computer image stabilization system is determined by the conditions of its operation. An example of a possible structural diagram of computer image stabilization algorithms for the azimuthal channel is shown in Fig. 4.

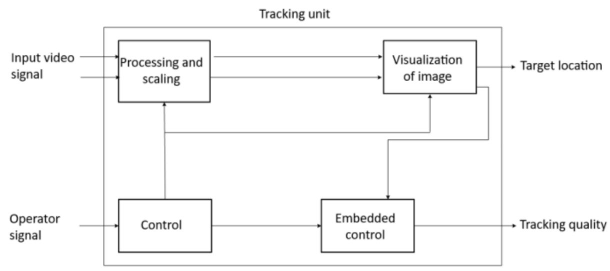

Fig. 4. Block diagram of computer image stabilization

The input video signal is fed to the primary processing unit, where, depending on the characteristics of the signal source and the specific technical implementation of the inertially stabilized platforms, the optical image is converted into a digital format, brightness and contrast are adjusted, image compression is performed.

The obtained results are used as input data for the algorithm for selecting a limited area corresponding to the line-of-sight image.

Next, the algorithm for determining the discrepancy between the current and specified position of the line of sight operates. The external low-frequency tracking circuit processes these signals and rotates the optical device in the direction of movement of the observation object.

IV. SYNTHESIS OF GIMBALS INNER LOOP

The dynamic equations of an electric motor with a gimbal frame can be written in the following form

$$\begin{aligned} &\tau \frac{dT}{dt} + T = K_M L_{PWM} - M_{CF}(\varpi), \\ &J\frac{d\omega}{dt} = T - M_{VF}(\varpi), \end{aligned} \tag{1}$$

where $M_{VF}(\varpi) = f_v \varpi$ is the moment of viscous friction; T the torque created by an electric motor; L_{PWM} is the instantaneous value of impulse width.

Now it is possible to formulate the problem of the synthesis of the law of control of the internal stabilization loop for the model (1). Since the main purpose of the problem is disturbance ω_d suppression, the theory of minimization of the L_2-gain coefficient can be used to solve it. Let us determine the amplification factor of the system, limited by the modulus γ, as follows [5]:

$$L_2 = \frac{\int_0^\infty \left\| y(t) \right\|^2 dt}{\int_0^\infty \left\| \omega_d(t) \right\|^2 dt} \le \gamma^2. \tag{2}$$

When inequality (2) is satisfying, it is possible to determine the possibly minimal value γ^* that

$$\left\| W_{y\omega_d}(s) \right\|_\infty \le \gamma^*, \tag{3}$$

where $\left\| W_{y\omega_d}(s) \right\|_\infty$ is H_∞ norm of the transfer function $W_{y\omega_d}(s)$ from the disturbance ω_d to the system's output $y = \omega$.

Thus, the value γ is a measure of the suppression of external disturbances ω_d that is the ultimate goal of the functioning of the stabilization loop. Therefore, it is advisable to choose the PI control law for the feedback circuit of the inertially stabilized platform [1]

$$K_{con} = K_p + K_i \cdot s^{-1}, \tag{4}$$

where K_p, K_i are proportional and integral gains, respectively.

It is necessary to find some optimal coefficients K_p , K_i in the control law (4) without direct connection, that is, when the direct connection gain coefficient K_{ff} is equal to zero. Since the goal of control synthesis is the minimization of the L2 gain (2), (3), it is necessary to minimize the expression $\|W_{y\omega_d}(s, K_{con})\|_2$ representing the H2 norm of the transfer function from the disturbance ω_d to the output ω, as well as the expression representing the H∞ norm of the same transfer function. The optimization criterion can be represented in the form of the combined objective function [6] – [8]

$$J = \lambda_2 \left\| W_{y\omega_d}(j\tilde{\omega}, K_{con}) \cdot W_{wf}(j\tilde{\omega}) \right\|_2 + \lambda_\infty \left\| W_{y\omega_d}(j\tilde{\omega}, K_{con}) \cdot W_{wf}(j\tilde{\omega}) \right\|_\infty + PF. \quad (5)$$

In expression (5), it is necessary to use the weighted transfer function $W_{wf}(j\tilde{\omega})$ to estimate the norms in the practically realized frequency bandwidth $\tilde{\omega} \le 200$ rad/s, which is of great importance for the digital version of the algorithm presented below. The bandwidth is limited by the condition of the Kotelnikov–Shannon discretization theorem, which in practical situations is implemented with the help of pre-pulse filtering [9]. This condition requires the selection of a weight transfer function in the form:

$$W_{wf}(j\tilde{\omega}) = \frac{1}{2.54 \cdot 10^{-6} s^2 + 3.8 \cdot 10^{-3} s + 1}. \quad (6)$$

Now the optimization procedure can be formulated as follows:

$$\text{Find } \arg\min_{K_{con}} J(K_{con}), \text{ subject to}: K_{con} \in D_p, \quad (7)$$

where D_p is the range of permissible values n the plane of the controller parameters, which is determined by the penalty function *PF*. After performing the optimization procedure (7) taking into consideration the penalty function (6), the following parameters of the regulator were obtained:

$$K_p = 62.25, \; K_i = 9.64.$$

The corresponding values of the norms make up

$$\left\| W_{dy}(j\tilde{\omega}, K_{con}) \right\|_2 = 0.43, \; \left\| W_{dy}(j\tilde{\omega}, K_{con}) \right\|_\infty = 0.047.$$

Such values confirm a good ability to suppress external disturbances ω_d. The eigenvalues of the closed system are equal to: ($-81.1 \pm j3584$, -0.2). This means that the system is very "hard", as noted earlier. The high-frequency complex poles of the closed system are explained by the above-mentioned eigenvalues of the matrix in the model of the control object (1), and the low-frequency real pole appears due to the integral gain of the regulator [10] – [12].

The simulation results allow us to assess the effectiveness of the inertially stabilized platform in tracking mode under a reference signal with a step input of 0.25 rad/s. This signal corresponds to the linearly increasing azimuth command signal coming from the external circuit. Transitional processes for this case are shown in Figs 5 and 6. Figure 5 presents the transient process according to the output coordinate of the inertially stabilized platform, and Figure 6 shows the transient process according to the control signal (the pulse width of the PWM converter).

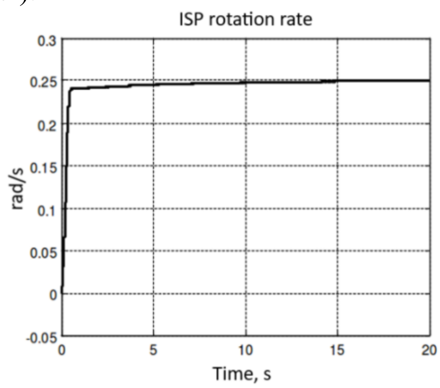

Fig. 5. The transient process on the rotation rate

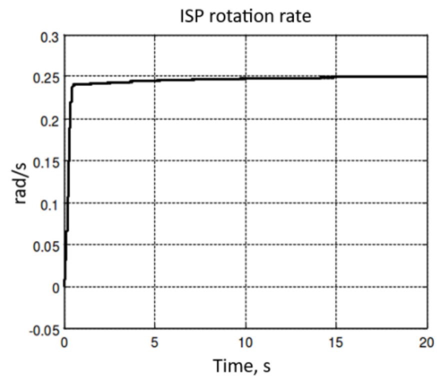

Fig. 6. The transient process on the output signal

The graphs presented in Figs 5 and 6 demonstrate a quick reaction of the control system of the inertially stabilized platform (see Fig. 5) and the absence of saturation at the control input (see Fig. 6), since $L_{PWM} < 2.5$ ms

V. Synthesis of the Control System for Gimbals Outer Loop

Let us pass on to the formulation of the problem of synthesizing the external tracking subsystem. To control the gimbals of the tracking loop, a torque motor with a transfer function as follows was selected as a rotary drive:

$$W_{MG}(s) = \frac{K_{M1}}{s(\tau_{el}s+1)(\tau_{em}s+1)}, \quad (8)$$

where τ_{el} and τ_{em} are the electric and electromechanical time constants of the electric motor, respectively, K_{M1} is the static gain of the torque motor, provided that the PWM pulse width is the input, and the motor torque is the output.

In accordance with the structural scheme presented in Fig. 1, and expression (8), the transfer function of the open tracking system can be written in the following form

$$W_{OL}(s) = \frac{1}{s}\cdot K_{con1}(s)W_{MG}(s)W_{ST}(s) = \frac{K_{con1}(s)K_{M1}K_{con}(s)W_{sg}(s)}{s^2(\tau_{el}s+1)(\tau_{em}s+1)[1+W_{sc}(s)\cdot W_{sg}(s)]}, \quad (9)$$

where $K_{con1}(s)$ is the transfer function of the tracking law. The transfer function of the open tracking system (9) includes two integrators. Thus, the tracking loop has the property of first-order astatism, that is, the established tracking error in the case of a linearly increasing command signal ψ_c is zero, and the integral component is redundant.

One of the goals of the synthesis is the simplicity of control algorithms. Therefore, the proportional-differential (PD) control law is the most suitable algorithm:

$$K_{con1}(s) = K_{\psi} + K_{\omega}s, \quad (10)$$

where K_{ψ} is the proportional or azimuthal gain coefficient, and K_{ω} is the differential coefficient or azimuthal velocity coefficient.

Since the inertially stabilized platform is equipped with angle and angular rate sensors, the implementation of this control law is the simplest of all possible. Since the structure of the control law (10) is assumed to be known from the very beginning, instead of the complex procedure of synthesis of the H∞ regulator [7], it is possible to apply a much simpler procedure of parametric optimization with the following complex indicator "quality - robustness" for the tracking loop [6]

$$J_t = \lambda_S \|S(j\tilde{\omega})\|_{\infty} + \lambda_T \|T_C(j\tilde{\omega})\|_{\infty} + PF_t, \quad (11)$$

where $S(j\tilde{\omega})$ is the sensitivity function of the system; $T_C(j\tilde{\omega})$ is the complementary sensitivity function; $\lambda_S = 10$ and $\lambda_S = 10$ are weight coefficients. Minimization of indicator (11) is equivalent to finding a compromise between robustness and quality of the control system.

Execution of the optimization procedure with the quality indicator (11) leads to the control law:

$$K_{con1}(s) = 0.645 + 0.323\cdot s,$$

and to the following norm values: $\|S(j\tilde{\omega})\|_{\infty}$ = 1.001, $\|T_C(j\tilde{\omega})\|_{\infty}$ = 0.02. Thus, the quality of the system is quite acceptable, while the robustness of the system is very high. The tracking error of the synthesised system is represented in Fig. 7.

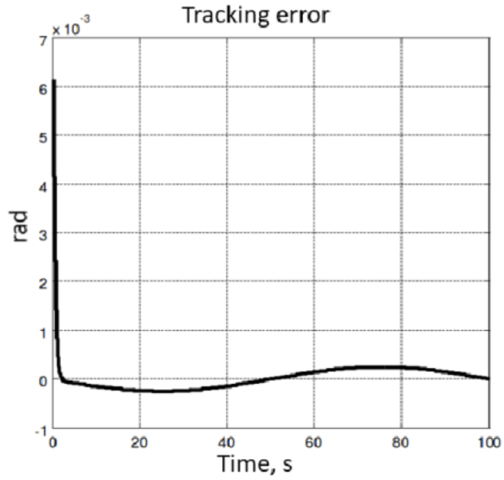

Fig. 7. The tracking error of the outer control loop

VI. CONCLUSIONS

The synthesis of control with direct feedback on disturbance is carried out based on the theory of invariance, and the synthesis of the control law with feedback is performed by the method of minimization of the gain coefficient in accordance with the specifics of its application in the inertially stabilized platform.

Taking into account the specific dynamic properties of stabilizing and tracking control loops, it is reasonable to choose a PI controller for the stabilization loop and a PD controller for the tracking loop. To determine the parameters of the PD regulator, a simplified version of control based on the minimization of the complex indicator "robustness-quality" was chosen

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Sushchenko Olha. ORCID 0000-0002-8837-1521. Doctor of Engineering. Professor.
Faculty of Air Navigation, Electronics and Telecommunications, State University "Kyiv Aviation Institute", Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine (1980).
Research area: motion control and inertial navigation systems.
Publications: 351.
E-mail: sushoa@ukr.net

Dyvnych Mykola. ORCID 0009-0000-6260-0069. Candidate of Engineering Science. Associate Professor.
Faculty of Air Navigation, Electronics and Telecommunications, State University "Kyiv Aviation Institute", Kyiv, Ukraine.
Education: Kyiv Institute of Engineers of Civil Aviation, Kyiv, Ukraine, (1975).
Research area: inertial and laser measuring instruments, control systems.
Publications: 90.
E-mail: npdvn@gmail.com

О. А. Сущенко, М. П. Дивнич. Проектування систем керування із двовісним кардановим підвісом для стабілізації об'єктів спостереження

У статті представлено особливості проектування двовісної інерційної стабілізованої платформи, призначеної для стабілізації пристроїв та пристроїв спостереження, наприклад, камер. Проаналізовано проблему стабілізації зображень, включаючи електромеханічні, оптичні, механічні та комп'ютерні методи. Представлено відповідні структурні схеми. Представлено процедуру синтезу внутрішнього та зовнішнього контурів стеження системи керування. Запропоновано структуру законів керування. Представлено комбіновані критерії оптимізації, що забезпечують компроміс між точністю стеження та стійкістю до збурень кутової швидкості. Описано структури синтезованих регуляторів. Наведено результати моделювання синтезованої системи. Наведено аналіз результатів моделювання. Розраховано норми системи. Отримані результати можуть бути використані в галузі стабілізації широкого класу приладів, призначених для роботи на рухомих об'єктах.

Ключові слова: двовісні карданні підвіси, стабілізація; система стеження; регулятор; моделювання; підхід до проектування.

Сущенко Ольга Андріївна. ORCID 0000-0002-8837-1521. Доктор технічних наук. Професор.
Факультет аеронавігації, електроніки та телекомунікацій, Державний університет «Київський авіаційний інститут», Київ, Україна.
Освіта: Київський політехнічний інститут, Київ, Україна, (1980).
Напрям наукової діяльності: системи стабілізації інформаційно-вимірювальних пристроїв.
Кількість публікацій: 351.
E-mail: sushoa@ukr.net

Дивнич Микола Полікарпович. ORCID 0009-0000-6260-0069. Кандидат технічних наук. Доцент.
Факультет аеронавігації, електроніки та телекомунікацій. Державний університет «Київський авіаційний інститут», Київ, Україна.
Освіта: Київський інститут інженерів цивільної авіації, Київ, Україна, (1975).
Напрям наукової діяльності: інерціальні та лазерні вимірювальні прилади, системи керування.
Кількість публікацій: 90.
E-mail: npdvn@gmail.com