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METHODOLOGY OF DEVELOPMENT OF AN ADAPTIVE STABILIZATION SYSTEM FOR EQUIPMENT OF UNMANNED VEHICLE

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Abstract—The article is devoted to the development of an adaptive stabilization system for equipment installed on unmanned ground vehicles operated in extreme impassable or difficult-to-pass conditions, which determine the nature and specificity of the impact of disturbances on the installed equipment. The article considers a mini-class unmanned ground vehicles, and a four-wheeled platform is considered as a simplified model of such a vehicle. As extreme impassable or difficult-to-pass traffic conditions, terrain with a complex profile, additional impulse disturbances that simulate hills and pits, and the slope of the traffic surface are considered. A two-axis stabilization system with classic PI controllers in the stabilization channels relative to the transverse and longitudinal axes is used as the base. The modeling and analysis of the basic system showed that in the described conditions of the unmanned ground vehicles movement, the stabilization errors in both channels exceed the permissible values, and taking into account the nonlinearities and possible changes in inertial characteristics, such a system becomes inoperable. To develop the adaptive system, the method of Model Reference Adaptive Control with additional damping of parameters was used. Based on this method, an adaptive PI controller was developed for use in the channels of the stabilization system relative to the transverse and longitudinal axes. The adaptive system was simulated in extreme impassable or difficult-to-pass conditions of the unmanned ground vehicles movement, taking into account the influence of nonlinearities in the engine and gearbox, as well as taking into account the increase in the load on the gearbox shaft by 2 and 3 times compared to the adopted design value. It is shown that the stabilization errors of the adaptive system in both channels do not exceed the established permissible value, and the presence of nonlinear characteristics and a change in the load do not lead to a decrease in the accuracy of the adaptive stabilization system.

Keywords—Unmanned vehicle, stabilization system, controller, adaptive control, simulation.

I. INTRODUCTION

Today, unmanned vehicles are used in various physical environments with specific operating conditions and dynamic influences that determine the characteristics of their movement, the need to overcome obstacles, and the requirements for stability and maneuverability. Among unmanned ground vehicles (UGV), wheeled vehicles are widely used, which have the following advantages: the cheapest development among other types; ease of control and balancing; a wide range of movement speeds; maneuverability. But, at the same time, there are problems in overcoming obstacles when moving over terrain with a complex profile, on off-road, sandy and viscous surfaces. Wheeled UGVs are equipped with equipment for various purposes, for the effective use of which it is necessary to ensure stabilization with appropriate accuracy indicators in

a wide range of UGV speeds, conditions and terrain profile.

The problem of equipment stabilizing on unmanned vehicles remains relevant, despite significant progress in the development of automatic control methods and systems. To solve this problem, it is necessary to take into account the type of unmanned vehicle, the conditions and modes of its movement, which determine the nature and specifics of the impact of disturbances on the installed equipment, as well as the requirements for the stabilization system imposed by the type and characteristics of this equipment. Such systems must provide acceptable accuracy of spatial stabilization of equipment under various disturbances accompanying the operation of the facility in real conditions, as well as under conditions of uncontrolled changes in the inertial characteristics of the equipment.

II. PROBLEM STATEMENT

Among UGVs, the most common are those with four wheels [1], [2]. Their advantage is stability and the ability to implement classic steering with swivel wheels on one of the axles.

In robotics, one of the important parameters for the systematization of robots is their dimensional characteristics, which take into account the dimensions, mass and overall physical scale of the platform. According to the classification [3], there are five main classes: micro, mini, medium, large and super-large robots. These categories cover almost the entire spectrum of robotic systems, including UGV. Mini UGVs [3] have dimensions ranging from 0.1 m to 0.5 m and a mass of up to 10 kg. These are the most common UGVs for internal logistics, inspections, covert missions and experimental research. Wheeled UGVs of this class demonstrate high maneuverability indoors and can operate in confined spaces. Mini UGVs are equipped with compact observation and navigation equipment that is sensitive to angular body oscillations and vibrations. For such equipment, manufacturers impose strict requirements for spatial position accuracy: the permissible angular instability is 0.02° – 0.1° , the range measurement error is within 1–2%, and the linear positioning error is no more than 0.02 m.

At the same time, small-sized wheeled UGVs can be operated in extreme impassable or difficult-to-pass conditions, for example, on hilly and rugged terrain with a high degree of unevenness, areas with heterogeneous soil and inclusions with different degrees of density, with elevation differences [4], [5]. Therefore, the influence of the terrain profile on the deviation of the equipment installation location from the given spatial position is decisive.

The analysis of modern publications has shown the presence of a significant number of works that are the contribution of researchers to the development of methods and systems of automatic control, in particular stabilization systems. They also take into account the trends in the development of such systems based on the use of adaptive and robust control methods, fuzzy logic controllers, artificial intelligence methods [6] – [10].

But the processes of equipment stabilization under the complex influence of irregular disturbances of varying intensity, which is typical for extreme impassable or difficult-to-pass operating conditions of UGVs, are insufficiently studied. For stabilization systems of small-sized wheeled UGVs equipment, there are restrictions on the use of

functional elements. When selecting them, it is necessary to take into account both accuracy, speed, reliability, and weight and dimensions. Existing stabilization systems are not adapted to work with variable inertial characteristics of equipment without constant additional settings of regulators, and mathematical algorithms for increasing accuracy require high computing power.

Classical PI and PID controllers do not provide the required quality in such conditions, and systems based on them are not able to automatically compensate for changes in inertia, load torque, the influence of dry friction, backlash, degradation of engine characteristics, and changes in the spectral composition of disturbances. Therefore, we propose to develop an adaptive stabilization system to ensure acceptable accuracy of equipment stabilization in extreme impassable or difficult-to-pass conditions of movement of small-sized wheeled UGVs, as well as taking into account the influence of nonlinear system characteristics and possible changes in the inertial characteristics of the equipment. To develop an adaptive stabilization system, we propose to use the adaptive control method of Model Reference Adaptive Control (MRAC) [11], [12]. The method consists in comparing the response of a real object with the response of a reference model that describes the desired dynamics. If a deviation occurs between the outputs, the adaptive law automatically changes the controller parameters in such a way as to minimize this discrepancy.

The main goal of the article is to simulate and analyze a stabilization system with an adaptive controller based on MRAC in extreme impassable or difficult-to-pass conditions of movement of a small-sized wheeled UGV, taking into account the influence of nonlinear system characteristics and changes in the inertial characteristics of the equipment.

III. MODEL OF THE WHEELED UGV AND ITS DRIVING CONDITIONS

We consider a mini-class UGV, the dimensions of which in three dimensions do not exceed 0.5 m, and the weight of the installed equipment does not exceed 5 kg. As a simplified model of such a UGV, we consider a four-wheeled platform, and let OXYZ be the coordinate system associated with the platform as shown in Fig. 1. The center of the coordinate system O is aligned with the center of mass of the platform, the OY axis is directed along the longitudinal axis, the OX axis is directed along the transverse axis, and the OZ axis is directed along the vertical axis of the platform.

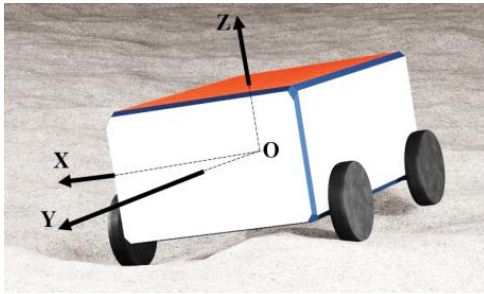


Fig. 1. Coordinate system associated with the model of UGV

We consider the movement of the platform at a constant speed of 5 km/h (1.4 m/s). As a source of disturbance for equipment installed on a wheeled UGV, we consider the terrain profile of the UGV's movement surface. The road profile can be described by a random function of the dependence of the terrain irregularities on the distance traveled, where the height of the irregularities is a random variable with a normal probability distribution. The classification of roads by the level of irregularities is given in the ISO 8608 standard, which describes random irregularities as a function of spatial frequency (number of oscillations per meter of path) and characterizes them based on the power spectral density S_0 [13].

Extreme impassable or difficult-to-pass traffic conditions include the following: terrain with a complex profile and additional impulse disturbances that simulate hills and pits; terrain with a complex profile and varying steepness of the climb [5], [13]. The sample of disturbance when driving on terrain with a complex profile (class F road) with two additional impulse disturbances, obtained over a time interval of 100s, is shown in Fig. 2.

An example of a disturbance when driving on terrain with a complex profile (class F road) and a slope of the driving surface along the longitudinal axis of the UGV at a time interval of 300s is shown in Fig. 3 [5].

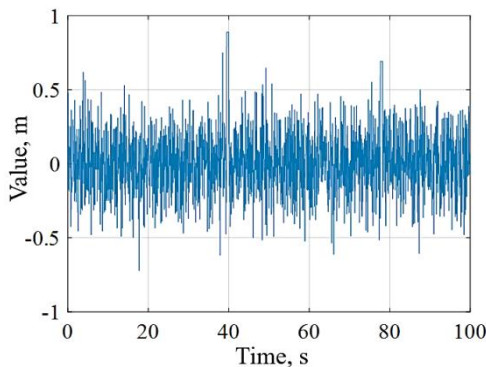


Fig. 2. Disturbance sampling for a class F road profile with two impulse disturbances

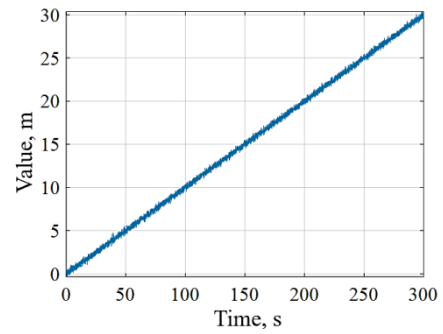


Fig. 3. Disturbance sampling for a class F road profile and a slope of the driving surface

In this case, it was taken into account that the speed of change in the height of the traffic surface is 0.1 m/s, which corresponds to a change in height of 30 m over a distance of 420 m traveled during the simulation (the angle of inclination of the traffic surface is 4.1°).

Thus, it is necessary to ensure stabilization of the equipment in the horizon plane with an error not exceeding 0.02° for the described above conditions of UGV movement.

IV. SIMULATION OF STABILIZATION SYSTEM BASED ON CLASSICAL PI CONTROLLER

We use a two-axis stabilization system with identical stabilization channels relative to the transverse and longitudinal axes of the UGV, and a classical PI controller in each channel, as shown in Fig. 4.

According to the above scheme, the angular deviations of the UGV model relative to the horizon plane α and β are due to the action of moments relative to the transverse and longitudinal axes (M_x and M_y) when the UGV moves over terrain with a complex relief profile. Simulation of the dynamics of angular inclinations of a small-sized UGV is given in [13]. The input (required) value of the angle of deviation of the platform with the equipment from the horizontal position is taken as zero. Then the output

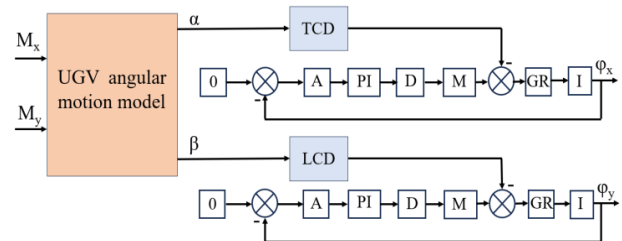


Fig. 4. Generalized structural diagram of the two-axis stabilization system: TCD is transverse channel of disturbance; LCD is longitudinal channel of disturbance; A is amplifier; PI is Proportional Integral controller; D is Derivative controller; M is electrical motor; GR is gear reducer; I is integrator

value of the closed loop of each of the stabilization channels is the angle of deviation of the platform from the horizontal position, therefore the output values φ_x and φ_y are the stabilization errors of the corresponding system channels.

The simulation of the two-axis linear stabilization system was carried out for UGV movement at a constant speed of 5 km/h over terrain with a complex profile (class F road) with two additional impulse disturbances, as well as terrain with a complex profile (class F road) and a slope of the movement surface along the longitudinal axis of the UGV.

The simulation results showed that under the action of impulse disturbances against the background of a class F road profile, the stabilization errors in both channels have close

values, the deviations from the horizon plane along each axis do not exceed $4 \cdot 10^{-5}$ rad (approximately 0.0023°) and are within acceptable limits.

For the second simulation case, it is taken into account that the variable surface steepness affects only the deviation of the longitudinal axis of the platform with the equipment relative to the horizon plane. Accordingly, this disturbance is fed into only one stabilization channel, while the effect of the disturbance from the unevenness of the road profile and obstacles is taken into account in both channels. Samples of the output signals φ_x and φ_y under the action of an obstacle with a duration of 2s against the background of a class F road profile and a road surface slope of 4.1° are shown in Fig. 5.

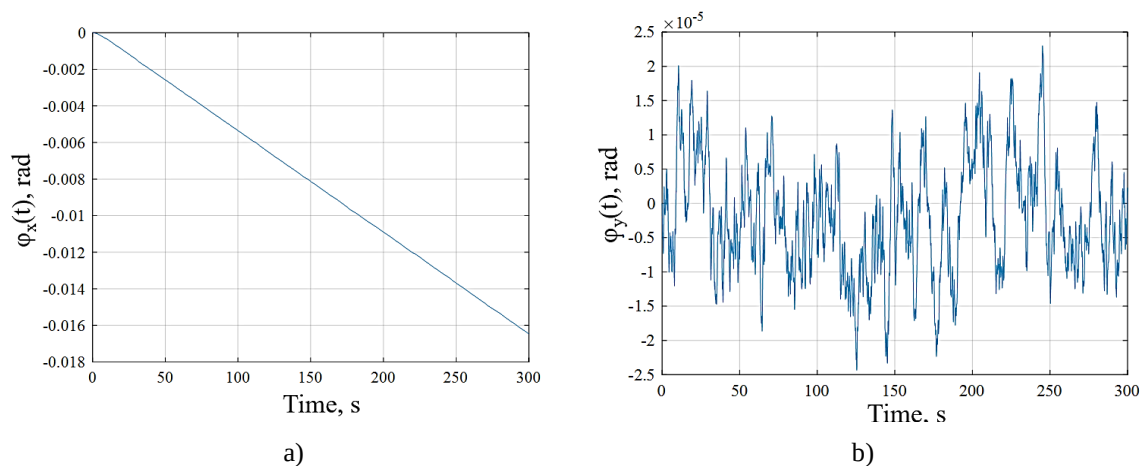


Fig. 5. Stabilization errors when moving over terrain with a complex profile and slope: (a) relative to the transverse axis; (b) relative to the longitudinal axis

The obtained results show that on terrain with a complex profile and slope, the error in the stabilization channel relative to the transverse axis reaches a value of 0.97° , which does not meet the requirements.

In addition to the considered difficult conditions of UGV movement, the stabilization error will be affected by other adverse factors, such as nonlinear system characteristics or variable characteristics of the useful equipment. Changes in the inertial characteristics of a platform with equipment can be caused by the following factors: operational increase in the weight of the installed equipment; shift of the center of gravity when moving on a surface with different slope steepness; engine degradation or mechanical wear, which directly leads to an increase in the load on the output shaft. Under the conditions described above, classical PI and PID controllers mostly do not provide the required control quality. Therefore, we propose the development of an adaptive system to ensure the stabilization accuracy

requirements in extreme impassable or difficult-to-pass UGV driving conditions and in the presence of other adverse factors.

V. SYNTHESIS AND SIMULATION OF AN ADAPTIVE STABILIZATION SYSTEM

To synthesize an adaptive system, we will use the Model Reference Adaptive Control (MRAC) method [11], [12], [14]. The method is based on comparing the response of a real object with the response of a reference model that describes the desired dynamics. If there is a deviation between them, the adaptive law automatically changes the controller parameters in such a way as to minimize this deviation. We will use this method for the considered system with a PI controller to ensure automatic changes in the coefficients K_p and K_i when the characteristics and conditions of the UGV movement change. Additionally, we use adaptation with damping of parameters to ensure stability in the presence of encoder noise, nonlinearity of the stabilization

system drives, and high-frequency disturbance components.

We write the adaptation equations for the coefficients of the PI controller in the form:

$$\begin{aligned}\dot{\Delta K}_p &= -\gamma_p \cdot e \cdot e_1 - \zeta_p \Delta K_p, \\ \dot{\Delta K}_I &= -\gamma_I \cdot e \cdot \int e dt - \zeta_I \Delta K_I,\end{aligned}$$

where $\Delta K_p, \Delta K_I$, are adaptive increments according to the coefficients K_p and K_I ; e is stabilization error; e_1 is feedback after correction; γ_p, γ_I are adaptation speeds of the corresponding coefficients; ζ_p, ζ_I are damping coefficients.

Let's take into account the constraints to determine the maximum and minimum level of adaptation of coefficients:

$$\begin{aligned}\Delta K_p &= \text{sat}\left(\int \dot{\Delta K}_p, dt^\circ \pm dK_{p_{\max}}\right), \\ \Delta K_I &= \text{sat}\left(\int \dot{\Delta K}_I, dt^\circ \pm dK_{I_{\max}}\right).\end{aligned}$$

Then the coefficients of the PI controller are obtained by the expressions:

$$K_p = K_{p_0} + {}^\circ \Delta K_p \text{ and } K_I = K_{I_0} + {}^\circ \Delta K_I,$$

where K_{p_0}, K_{I_0} are the initial values of the coefficients of the PI controller, respectively.

We use the following numerical data in order to determine the coefficients of the adaptive PI controller:

- as the initial values of K_{p_0} and K_{I_0} we take the values of the coefficients of the used classical controller $K_{p_0} = 0.95$ and $K_{I_0} = 0.1$;
- we choose the adaptation limits $dK_{p_{\max}} = 0.3K_{p_0}$ and $dK_{I_{\max}} = 0.3K_{I_0}$ taking into account the negative impact of too large values on the stability of the system;
- adaptation speeds of the corresponding coefficients $\gamma_p = 6 \cdot 10^{-5}$ and $\gamma_I = 4 \cdot 10^{-5}$ are selected based on the simulation results for different values of dry friction, backlash, and load moment on the motor shaft;
- damping coefficients are $\zeta_p = 0.009$ and $\zeta_I = 0.0063$.

Thus, the developed adaptive PI controller is a serial connection of the classical PI controller we used and the subsystem for tuning the controller coefficients in real time based on the MRAC method. The control action is formed at the output of the adaptive PI controller in accordance with the law

$$u(t) = K_p(t)e(t) + K_I(t) \int e(t) dt,$$

and is fed to the D controller.

The modeling scheme of an adaptive PI controller based on the MRAC method is shown in Fig. 6.

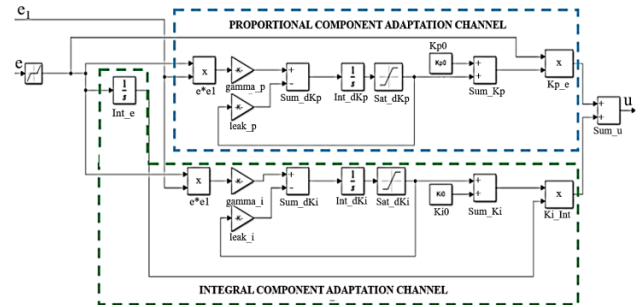


Fig. 6. Modeling scheme of an adaptive PI controller

According to the above scheme, in each of the channels, the error multiplication block e by the feedback signal e_1 after correction (after the D controller) generates an excitation signal for the adaptive law. Multiplication by the adaptation speed sets the intensity of the parameter change, while multiplication by the damping coefficient stabilizes the parameter and prevents drift. The saturation block limits the adaptation value within the range of $\pm 30\%$ of the nominal value. The current value of the coefficient is formed by an adder, which adds an adaptive increment to the initial value.

We will perform simulation and analysis of the effectiveness of the equipment stabilization system for a two-axis system with a developed adaptive PI controller in extreme impassable or difficult-to-pass conditions of UGV movement, taking into account the nonlinearities of the system drives and changing the inertial characteristics of the platform with the equipment.

As difficult-to-pass conditions for UGV movement, we consider the above-described conditions of movement on terrain with a complex profile (class F road), additional impulse disturbances with a duration of 2s, simulating pits and hills, and with a road surface slope of 4.1° .

In the generalized structural diagram of the system shown in Fig. 4, we will use the developed adaptive PI controller instead of the classical one presented there, and we also take into account the nonlinearities in the motor and gearbox, caused by the dead zone of the static characteristic (the gearbox backlash is 0.02 rad) and the dry friction torque of 0.02 N·m.

We also take into account the changing of the moment of load on the stabilization platform drives due to the influence of external factors, for example, when the UGV moves over complex uneven terrain, when hitting obstacles, changing the position of the body, working with various attachments, as well as during moments of sharp maneuvering or acceleration. As noted earlier, this can lead to an instant increase or decrease in the moment of inertia and the equivalent load applied to the gearbox and

motor of the stabilization system. To adequately simulate the operation of the stabilization system drives in such conditions, the model implements switching of the moment of inertia during simulation. This is done programmatically using a logic block that changes the coefficient in the motor link depending on time and allows to simulate an increase in the equivalent load on the gearbox shaft by 2 and 3 times compared to the adopted design value (up to 5 kg).

The results of simulation a two-axis adaptive system are shown in Figs 7 and 8 taking into account nonlinearities and changes in the nominal load under the action of a complex disturbance. The load increase occurs at 50 seconds of modeling. The samples of the system output signals characterize the change in time of the angles of deviation of the platform from the horizontal position relative to the transverse axis (Fig. 7) and relative to the longitudinal axis (Fig. 8) and are stabilization errors. Based on the

obtained data, the maximum values of the stabilization error are calculated for each channel, the value of which does not exceed the permissible value of 0.02° . In particular, when the load is increased by 3 times, the following maximum values of stabilization errors were obtained: relative to the transverse axis 0.015° and relative to the longitudinal axis 0.018° .

The results of simulation a two-axis adaptive system are shown in Fig. 9 taking into account nonlinearities and changes in the nominal load under the action of a complex disturbance and the slope of the motion surface. The influence of the surface slope is considered only on the deviation of the longitudinal axis from the horizon plane (relative to the transverse axis), therefore this factor is taken into account only in one stabilization channel. The simulation took into account the maximum possible increase in load of 3 times from the previously considered values for 50 seconds of simulation.

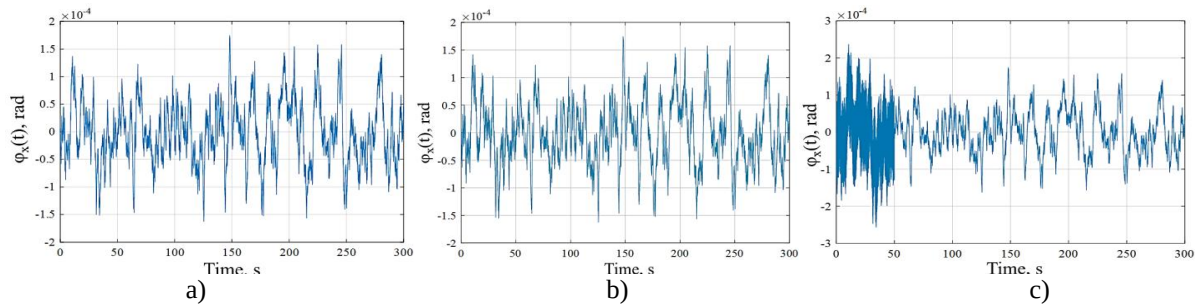


Fig. 7. Dependences of the stabilization error relative to the transverse axis under the action of a complex disturbance and taking into account nonlinearities for the calculated load (a) and increasing the load by 2 times (b) and by 3 times (c)

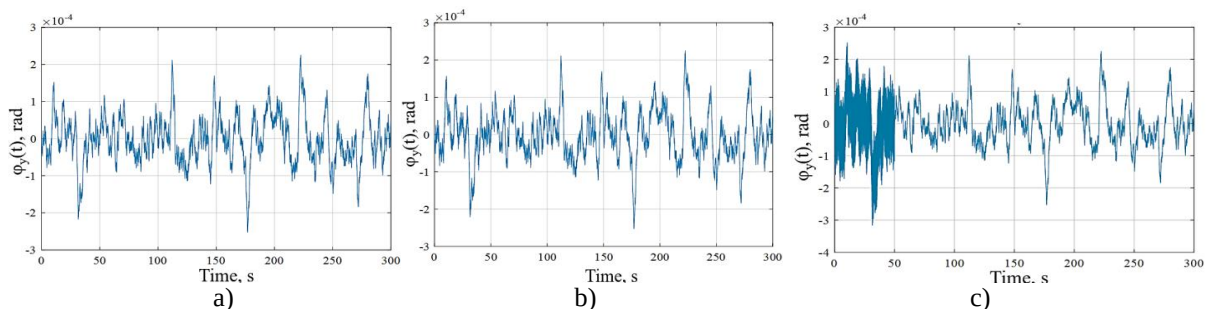


Fig. 8. Dependences of the stabilization error relative to the longitudinal axis under the action of a complex disturbance and taking into account nonlinearities for the calculated load (a) and increasing the load by 2 times (b) and by 3 times (c)

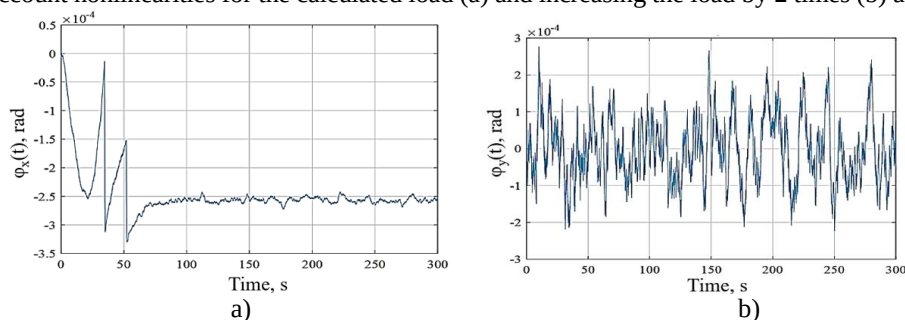


Fig. 9. Dependences of the stabilization error relative to the transverse axis (a) and to the longitudinal axis (b) under the action of a complex disturbance, the slope of the motion surface, and taking into account nonlinearities and increasing the load by 3 times

The obtained results show that the error in the stabilization channel relative to the transverse axis reaches a maximum value of 0.019° , and the error in the stabilization channel relative to the longitudinal axis reaches a maximum value of 0.016° . This indicates an acceptable accuracy of the two-axis stabilization system with an adaptive controller when the UGV moves under the described conditions.

Thus, the results of the research of the developed two-axis adaptive stabilization system for UGV equipment demonstrate that the adaptive system provides the necessary accuracy when moving the UGV over terrain with a complex profile and impulse disturbances, with variable slope steepness and under the influence of such adverse factors as nonlinearity of system characteristics or changing characteristics of useful equipment. Stabilization errors on both channels do not exceed the established permissible value of 0.02° , the presence of nonlinear characteristics and a 3-fold change in load do not lead to a decrease in the accuracy of the adaptive stabilization system.

VI. CONCLUSIONS

A stabilization system for installed equipment has been substantiated and improved on the base of adaptive control for small-sized wheeled UGVs operated in extreme impassable or difficult-to-pass traffic conditions.

A study of a two-axis linear stabilization system with a classic PI controller in each channel showed that stabilization errors significantly exceed permissible values when the UGV moves over terrain with a complex profile, additional impulse disturbances, and with a slope (relative to the transverse axis). The deviation of the platform with the equipment from the given spatial position is also affected by the nonlinearity of the system characteristics and possible changes in the inertial characteristics of the platform with the equipment.

To improve the system, an adaptive PI controller was developed based on the Model Reference Adaptive Control method with additional parameter damping to ensure automatic change of the controller coefficients when the characteristics and driving conditions of the UGV change. Simulation of a two-axis nonlinear stabilization system with an adaptive PI controller showed that the stabilization error relative to the longitudinal axis does not exceed 0.015° , and relative to the transverse axis does not exceed 0.018° in conditions of UGV movement over terrain with a complex profile and additional impulse disturbances even with a 3-fold increase in load. Also, the stabilization error relative

to the longitudinal axis does not exceed 0.016° , and relative to the transverse axis does not exceed 0.019° when the UGV moves over terrain with a complex profile, additional impulse disturbances and surface slope with a 3-fold increase in load.

The obtained results are new and indicate that the developed adaptive stabilization system for small-sized wheeled UGV equipment provides the necessary accuracy and expanded functionality in extreme impassable or difficult-to-pass UGV driving conditions.

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Н. І. Буряу, А. В. Осовцев, А. М. Довгополюк. Методологія розробки адаптивної системи стабілізації обладнання безпілотного транспортного засобу

Статтю присвячено обґрунтуванню та розробці адаптивної системи стабілізації обладнання, яке встановлюється на наземних безпілотних транспортних засобах (НБТЗ), що експлуатуються в екстремальних непрохідних чи важко прохідних умовах, які обумовлюють характер та специфіку впливу збурень на встановлене обладнання. В статті розглянуто НБТЗ класу міні, а чотириколісна платформа розглядається як спрощена модель такого засобу. У якості екстремальних непрохідних чи важко прохідних умов руху розглядається місцевість зі складним профілем, додатковими імпульсними збуреннями, що моделюють пагорби та ями, нахилом поверхні руху. Як базову використано двовісну систему стабілізації з класичними ПІ-регуляторами в каналах стабілізації відносно поперечної та повздовжньої осей. Проведене моделювання та аналіз базової системи показав, що в описаних умовах руху НБТЗ похибки стабілізації в обох каналах перевищують допустимі значення, а з урахуванням нелінійностей та можливого змінювання інерційних характеристик така система стає непрацездатною. Для розробки адаптивної системи використано метод адаптивного керування з еталонною моделлю та з додатковим демпфуванням параметрів. На основі цього методу розроблено адаптивний ПІ-регулятор для використання в каналах системи стабілізації відносно поперечної та повздовжньої осей. Проведено моделювання адаптивної системи в екстремальних непрохідних чи важко прохідних умовах руху

НБТЗ з урахуванням впливу нелінійностей в двигуні та редукторі, а також з урахуванням збільшення навантаження на вал редуктора в 2 та в 3 рази порівняно з прийнятим розрахунковим значенням. Показано, що похибки стабілізації адаптивної системи за обома каналами не перевищують встановленого допустимого значення, а наявність нелінійних характеристик та зміна навантаження не призводять до зниження точності адаптивної системи стабілізації.

Ключові слова: безпілотний транспортний засіб, система стабілізації, регулятор, адаптивне керування, моделювання.

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