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Synthesis Method of Control System for Spatial Motion of Autonomous Underwater Vehicle

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Abstract

The article deals with to the synthesis of autonomous underwater vehicle spatial motion control system on the basis of the decomposition principle. The entire control system is divided into six control subsystems with separate degrees of freedom. In turn, each subsystem consists of three control loops: the thruster control loop, the vehicle's velocity control loop and the control loop of its position. The paper proposes different methods of synthesis of controllers for each of these loops. The mathematical simulation confirms that the synthesis strategy selected was correct and shows the high efficiency of the obtained control system.

Key words: *underwater vehicle; control system; adaptive system; self-tuning; sliding mode*

1. INTRODUCTION

In recent decades various types of autonomous underwater vehicles (AUV) have been created for the study of ocean depths. The focus has been made on fast and effective performance of standard and specific technological operations. To perform these operations, the AUV must approach the objects of work precisely and fast, as well as move precisely, with varying velocities, along complex spatial trajectories [1-7]. The quality of these works is greatly affected by the uncertainty and considerable variability of mass-inertia and hydrodynamic characteristics of the AUV, of the strong influence of its degrees of freedom, the inertia and nonlinearity of the thrusters which parameters also change [2, 4 and 6]. Therefore, in the synthesis of a control system (CS) for the AUV spatial motion it is necessary to consider all these features as much as possible.

Most promising for the control of AUV are robust CS. These CS provide for the independence of the control process from variations in parameters and the properties of the control object (CO). Variable structure systems (VSS), which work in a sliding mode, are a variety of robust CS [8, 9]. These systems were successfully used for AUV control [4, 10]. The main deficiency of traditional VSS is that, to provide for the sliding mode, when the parameters of the CO change, the VSS's parameters are calculated for the most loaded operation modes [8]. Therefore, a traditional VSS always has the lowest operating speed and work accuracy. For eliminating this deficiency in VSS, it is possible to introduce the elements of adaptation, which enable changing the parameters of switching taking into account the current values of the control object parameters. As a result, the operation speed of the system in more favorable modes of the AUV operation increases.

In many adaptive CS, the self-adjusting of controller is achieved on the basis of the measurement of the CO parameters. However, in moving AUV, many parameters can not be measured or identified. Therefore, this article proposes to use such algorithms of self-adjusting which make it possible to change the arrangement of switching surfaces in VSS and thus to increase the dynamic accuracy of control without any direct measurement of the AUV parameters [4, 10] in different modes of their operation.

2. TASK SETTING

Thus, this article formulates and solves the problem of high-quality (high-precision) AUV CS synthesis on the basis of their complete dynamic models which take into account negative effects of interaction among all the degrees of freedom, forces of the surrounding viscous fluid and the thruster complex dynamics.

These CS are synthesized on the basis of the decomposition method. According to this method, the entire AUV CS will be divided into separate subsystems for controlling its separate degrees of freedom. However, all interactions between all control channels will be preserved. Each control subsystem will consist of three loops: the internal control loop for the thrusters, the middle control loop for the AUV velocity and the external control loop for the spatial position of the vehicle. Each of these loops must ensure the stabilization of dynamic properties of the corresponding control object at a desired (nominal) level. This must considerably facilitate the task of synthesizing entire AUV CS.

3. MATHEMATICAL MODEL OF THE UNDERWATER VEHICLE

The most complete model of the AUV spatial motion dynamics consists of six nonlinear differential equations with variable parameters and interactions [2 - 4] which writing in following view:

$$
\begin{aligned}
&(m_a+\lambda_{11})\dot{\upsilon}_x - m_a Y_c\dot{\omega}_z + [(m_a+\lambda_{33})\upsilon_z + m_a Y_c\omega_x]\omega_y - \\
&-(m_a+\lambda_{22})\upsilon_y\omega_z = \tau_x + F_{gx} + F_{sx}, \\
&(m_a+\lambda_{22})\dot{\upsilon}_y + [(m_a+\lambda_{11})\upsilon_x - m_a Y_c\omega_z]\omega_z - \\
&-[(m_a+\lambda_{33})\upsilon_z + m_a Y_c\omega_x]\omega_x = \tau_y + F_{gy} + F_{sy}, \\
&(m_a+\lambda_{33})\dot{\upsilon}_z + m_a Y_c\dot{\omega}_x + (m_a+\lambda_{22})\upsilon_y\omega_x - \\
&-[(m_a+\lambda_{11})\upsilon_x - m_a Y_c\omega_z]\omega_y = \tau_z + F_{gz} + F_{sz}, \\
&(J_{xx}+\lambda_{44})\dot{\omega}_x + m_a Y_c\dot{\upsilon}_z + [-m_a Y_c\upsilon_x + (J_{zz}+\lambda_{66})\omega_z]\omega_y - \\
&-(J_{yy}+\lambda_{55})\omega_y\omega_z + [(m_a+\lambda_{33})\upsilon_z + m_a Y_c\omega_x]\upsilon_y - \\
&-(m_a+\lambda_{22})\upsilon_y\upsilon_z = M_x + M_{gx} + M_{sx}, \\
&(J_{yy}+\lambda_{55})\dot{\omega}_y + [m_a Y_c\upsilon_z + (J_{xx}+\lambda_{44})\omega_x]\omega_z + \\
&+[m_a Y_c\upsilon_x - (J_{zz}+\lambda_{66})\omega_z]\omega_x + [(m_a+\lambda_{11})\upsilon_x - m_a Y_c\omega_z]\upsilon_z - \\
&-[(m_a+\lambda_{33})\upsilon_z + m_a Y_c\omega_x]\upsilon_x = M_y + M_{gy} + M_{sy}, \\
&(J_{zz}+\lambda_{66})\dot{\omega}_z - m_a Y_c\dot{\upsilon}_x + (J_{yy}+\lambda_{55})\omega_y\omega_x - \\
&-[m_a Y_c\upsilon_z + (J_{xx}+\lambda_{44})\omega_x]\omega_y + (m_a+\lambda_{22})\upsilon_y\upsilon_x - \\
&-[(m_a+\lambda_{11})\upsilon_x - m_a Y_c\omega_z]\upsilon_y = M_z + M_{gz} + M_{sz},
\end{aligned} \tag{1}
$$

where m_a is the AUV mass; λ_{ij} is the diagonal matrix element of the added masses of liquid; J_{xx}, J_{yy}, J_{zz} are the moments of AUV inertia relative to its main axes of inertia; Y_c is the metacentric height; $\upsilon_x,\upsilon_y,\upsilon_z,\omega_x,\omega_y,\omega_z$ are the projections of linear and angular AUV velocities on the axis of a tied coordinate system; $\tau_x,\tau_y,\tau_z,M_x,M_y,M_z$ are the thrusts and moments created by the AUV thruster complex according to a corresponding degree of freedom; $F_{gx},F_{gy},F_{gz},M_{gx},M_{gy},M_{gz}$ are the projections of hydrodynamic forces and the moment of liquid affecting the AUV on the axis of a tied coordinate system; $F_{sx},F_{sy},F_{sz},M_{sx},M_{sy},M_{sz}$ are the projections of hydrostatic force and the moment of liquid affecting the AUV on the axis of a tied coordinate system.

In model (1) the following dependence of hydrodynamic forces on the value of the projections of AUV velocity on the axis of a joint coordinate system [2,11] is supposed:

$$F_g = -d_1\upsilon\sigma - d_2\upsilon|\upsilon|\sigma', \quad M_g = -d_1'\omega\sigma - d_2'\omega|\omega|\sigma'$$

where $d1$, d_2, d_1', d_2' are the hydrodynamic coefficients of viscous friction, which correspond to linear and quadratic dependences of flow forces (moments) on the AUV velocity; σ, σ' are the coefficients, which determine the nature of AUV interaction with liquid at different values of velocity (they take values of 0 or 1).

Since actual AUV motion takes place in an absolute coordinate system, we must add to equations (1) the kinematic relationships, which ensure a transfer from a joint coordinates system to an absolute one [2]:

$$\dot{x} = J(x)\upsilon, \tag{2}$$

where $\mathbf{x} = (x, y, z, \varphi, \psi, \theta)^T \in R^6$ is the AUV position and orientation vector in an absolute coordinate system; $\upsilon = (\upsilon_x, \upsilon_y, \upsilon_z, \omega_x, \omega_y, \omega_z)^T \subseteq R^6$ is the vector of the linear and angular AUV velocities projections on the axis of the coordinate system tied into it; φ, ψ, θ are the yaw, pitch and roll, respectively; $\mathbf{J}(\mathbf{x}) \in R^{6\times 6}$ is the matrix of conversions of one coordinate system into another [3].

The complete model (1), (2) is very complex and does not make it possible to obtain easily realizable but high-quality regulators. Therefore, to simplify the synthesis, it is expedient to use the method of decomposition. According to this method, the system (1), (2) is divided into six separate subsystems, which correspond to separate AUV degrees of freedom. Each of the subsystems preserves all interactions with the other five subsystems as well as all the influence of the surrounding viscous fluid.

In this paper it is suppose that control signal are formed by means of couple of thrusters which create the thrusts along three axes of joint coordinate system.

As a result, any of the three subsystems, which correspond to linear AUV degrees of freedom (for example, along the axis x), can be described by the following system of equations:

$$
\begin{aligned}
&\tau_x = f_\tau(\omega_d,\upsilon_L), \ m\dot{\upsilon}_x + d_1\upsilon_x\sigma + d_2\upsilon_x|\upsilon_x|\sigma' + f_x = \tau_x, \\
&\dot{x} = j\upsilon_x + \phi_\upsilon,
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
&f_x = -m_a Y_c\dot{\omega}_z + [(m_a+\lambda_{33})\upsilon_z + m_a Y_c\omega_x]\omega_y - \\
&-(m_a+\lambda_{22})\upsilon_y\omega_z - F_{sx}
\end{aligned}
$$

$m_{min} \le m \le m_{max}$, $d_{1min} \le d_1 \le d_{1max}$, $d_{2min} \le d_2 \le d_{2max}$,

$J_{min} \le J \le J_{max}$, $d_1'{}_{min} \le d_1' \le d_1'{}_{max}$, $d_2'{}_{min} \le d_2' \le d_2'{}_{max}$,

where $f_\tau(\omega_d, \upsilon_L)$ is the nonlinear function, which describes the thruster complex; ω_d is the rate of the thruster propeller rotation; υ_L is the speed of the displacement of enveloping fluid relative to the AUV along the screw axis; j is the corresponding diagonal matrix element $J(x)$; ϕ_υ is a term considering the cross couplings between the appropriate degrees of freedom and determined by kinematic relationships (2); $m = m_a + \lambda_{11}$. For the rotational degree of freedom the equations are similar (3).

It should be emphasized that the six separate equations of form (3) are not a simplification of a complete mathematical model (1), since all the external actions and interconnections among all the AUV degrees of freedom are completely preserved. This formal mathematical conversion is only necessary for the simplification of subsequent CS synthesis.

The thruster dynamics has a great effect on the AUV dynamics as a whole [12-15]. Therefore, in the synthesis of a high-precision AUV CS it is necessary to include the dynamics of these thrusters in the mathematical model of AUV motion. In this article the model of thruster, proposed in work [15], is used. This model takes a full account of a number of important special features of the screw interaction with the surrounding viscous fluid and takes the following form:

$$J_d\dot{\omega}_d + (k_m k_w / R)\omega_d + M_t = u(k_m k_y)/R,$$

$$\tau = F_\tau s_\tau |\omega_d|,\ M_t = F_m(s_\tau + H_1 C_r \omega_d)|\omega_d|,$$

$$s_\tau = p - sign(\omega_d)\sqrt{p^2 - q}\ ,$$
$$p = H_1\omega_d - \upsilon_p/2 + F_\tau\omega_d/(4\rho A_s),$$

$$q = H_1\omega_d(H_1\omega_d - \upsilon_p),\ H_1 = H + \delta_H sign(\omega_d)\ ,$$
$$\upsilon_p = \upsilon_L(1 + sign(\omega_d) sign(\upsilon_L))/2$$

$$J_{dmin} \le J_d \le J_{dmax},\quad F_{mmin} \le F_m \le F_{mmax},$$

where H_1 is the hydrodynamic propeller pitch; H is the geometric propeller pitch; δ_H is the hydrodynamic correction for the propeller pitch; F_τ, F_m are the generalized thrust and moment coefficients; C_r is the factor of profile losses of the screw; ρ is the density of enveloping fluid; A_s is the propeller-disk area; J_d is the inertia moment of the rotating part of the propeller taking into account the connected moment of the inertia of liquid; R is the effective resistance of the armature circuit of electric motor; k_m, k_w are the moment and counter-EMF coefficients of the direct current electric motor; k_y is the amplifier gain of power; u is the propeller control signal of a corresponding degree of freedom; s_τ is the absolute propeller slip; M_t is the moment on the propeller shaft; p, q, υ_p are the auxiliary variables.

Following the principle of decomposition, during the creation of AUV CS, we will construct a multilevel CS which consists of six motion control subsystems for each separate degree of freedom. As an initial mathematical model we will use equations (3) - (4). First let us examine the synthesis of a motion CS only on one of the linear AUV coordinates. The same algorithm will be used for the synthesis of CS for rotational degrees of freedom.

However, even after the preliminary decomposition, the AUV model (3), (4) is too complicated for the direct use in the vehicle control law synthesis. Therefore, it is expedient to divide the control subsystem of each AUV degree of freedom into three separate local control subsystems: the CS of the thruster complex, the CS of velocity and the CS of AUV position.

Fig. 1 shows the functional diagram of a separate control subsystem of one of AUV degrees of freedom. In this figure some indices are omitted for simplification.

Thus, the AUV CS synthesis is divided into three stages.

During the first stage, the control system of AUV thruster which ensures constant desired dynamic properties for each thruster is synthesized.

In the second stage, adaptive regulators (on the basis of VSS) of all local AUV velocity control subsystems for each degree of freedom are developed. These regulators must guarantee the independence of dynamic properties of the velocity loops from the AUV parameters and ensure maximal indicators for operation speed and control accuracy.

In the third stage, a complete control system for the AUV spatial motion is synthesized. It contains the synthesized local control subsystems for each separate degree of freedom. This spatial motion control loop will give the AUV desired dynamic properties and will provide for attaining the high quality of spatial movement.

4. SYNTHESIS OF THE THRUSTER CONTROL SYSTEM

As it was mentioned earlier, the first stage of the synthesis of a general AUV CS, involves the synthesis of its thruster CS. The main target at this stage ensures that nonlinear object with variable parameters (4) will have desired dynamic properties at any change of its parameters in assigned ranges.

Let us assign a desired linear equation of the thruster dynamics in the form:

$$\dot{\tau} = (\tau_d - \tau)/T_d\ , \tag{5}$$

where τ_d is the desired thrust value; T_d is the desired time constant of the thruster.

The synthesis of thruster CS will be carried out in two stages. During the first stage, a nonlinear regulator, which ensures the desired dynamic properties in the case, when its parameters are constant, is synthesized. The second stage involves the synthesis of the loop of signal self-tuning against a reference model for the stabilization of the dynamic properties of propeller at a desired level in close of a variation of its parameters in assigned ranges. This makes it possible to considerably decrease the signal of correction and not to put propellers in a saturation mode.

4.1. Synthesis of the nonlinear regulator

To simplify the synthesis procedure, let us reduce the system (4) to a more convenient form. For this purpose let us exclude the intermediate variables p and q and solve the system (4) relatively $\dot{\tau}$. As a result, we will obtain:

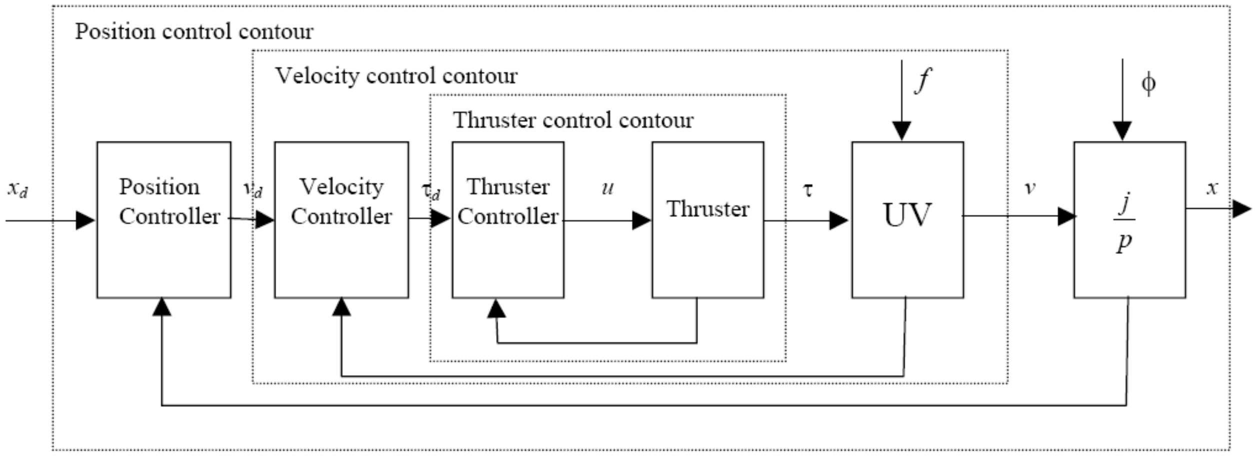

Figure 1. Functional diagram of a separate AUV control subsystem

$$\dot{\tau} = F_\tau D_\tau (k_m k_y u - k_m k_w \omega_d - \\ - RF_m |\omega_d| (s_\tau + H_1 C_r \omega_d))/(J_d R), \tag{6}$$

$$D_\tau = sign(\omega_d) \cdot s_\tau + |\omega_d| \cdot (k_1 + H_1 - sign(\omega_d) \times \\ \times \frac{k_1((2H_1 + k_1)\omega_d - \upsilon_p/2)}{\sqrt{(k_1\omega_d - \upsilon_p/2)^2 + 2H_1 k_1 \omega_d{}^2}}), \; k_1 = \frac{F_t}{4\rho A_s}$$

Since the synthesis of nonlinear regulator will be performed for the case, when the thruster parameters are constant, in the equation (6) let us accept that $F_m = F_{m0}$, $J_d = J_{d0}$.

For giving the thruster desired dynamic properties it is sufficient to select such a law of the control signal u change which will provide for the equality of the right sides of equations (5) and (6). After equating these parts and expressing control u, we will obtain the control law, which makes it possible to assign desired thruster dynamic properties with its nominal values:

$$u = (J_d (\tau_d - F_\tau |\omega_d| s_\tau)(T_d F_t D_\tau)^{-1} + k_m k_w R^{-1} \omega_d + \\ + F_m |\omega_d| (s_\tau + H_1 C_r \omega_d))R(k_m k_y)^{-1}. \tag{7}$$

4.2 Synthesis of the self-tuning loop

In the second stage the self-tuning loop which provides AUV thruster the desired dynamic properties (5) is synthesized. For retaining the high accuracy of the thruster work with the deviation of its parameters from nominal values we will use the approach proposed in work [16]. For this purpose let us introduce into the control law (7) the additional signal z of self-tuning. As a result, this control law will take the form:

$$u = (J_{d0} \frac{\tau_d - F_t |\omega_d| s_\tau}{D_\tau T_d F_t} + \frac{z}{D_\tau} + \frac{k_m k_w}{R} \omega_d + \\ + F_{m0} |\omega_d| (s_\tau + H_1 C_r \omega_d)) \frac{R}{k_m k_y}. \tag{8}$$

We will form signal z on the basis of difference between the signals τ and τ_m

$$e_m = \tau_m - \tau, \tag{9}$$

where signal τ_m is an output signal of a reference model:

$$\dot{\tau}_m = (\tau_d - \tau_m)/T_d. \tag{10}$$

For giving to the AUV thruster described by system (3) the desired dynamic properties of reference model (10) it is sufficient to ensure the stability of the system state in which $e_m \to 0$ with any values of parameters J_d and F_m the above ranges.

For the solution of this problem, we will apply a Lyapunov's method. For this, let us select the positively determined function $V = e_m^2/2$. As is known, the position of equilibrium $e_m = 0$ will be steady, if the condition $\dot{V} < 0$ is satisfied. Derivative V in view of equations (8-10) takes the form:

$$\dot{V} = e_m \dot{e}_m = e_m(\frac{(J_d - J_{d0})}{F_t} \dot{\tau}_m + (F_m - F_{m0}) D_\tau |\omega_d| \times \\ \times (s_\tau + H_1 C_r \omega_d) - z - \frac{J_{d0}}{T_d F_t} e_m) \frac{F_t}{T_d}. \tag{11}$$

We form signal z in the form:

$$z = h \cdot sign(e_m), \tag{12}$$

where $h > \max| \frac{(J_d - J_{d0})}{F_t} \dot{\tau}_m + (F_m - F_{m0}) D_\tau |\omega_d| (s_\tau + H_1 C_r \omega_d)|$. Let us show that in this case the stability condition $\dot{V} < 0$ will be always correct. If signal z is described by equation (12) then following inequality will be always true:

$$|z|>|\frac{(J_d - J_{d0})}{F_t}\dot{\tau}_m + (F_m - F_{m0})D_\tau|\omega_d|\times$$
$$\times(s_\tau + H_1 C_r\omega_d)|. \tag{13}$$

Since, according to expression (12), signs of signals e_m and z always coincide, then when $e_m > 0$ and $z > 0$ we may easily obtain:

$$\frac{(J_d - J_{d0})}{F_t}\dot{\tau}_m + (F_m - F_{m0})D_\tau|\omega_d|(s_\tau + H_1 C_r\omega_d) - z < 0,$$
$$-\frac{J_{d0}}{T_d F_t}e_m < 0. \tag{14}$$

From inequalities (14) and expression (11) it directly follows that $\dot{V} < 0$. When $e_m < 0$, the proof is carried out is a similar way.

In accordance with expressions (14) the h value will always have the highest possible value. This can lead to reaching the zone of saturation by the amplifier and to the loss of the system controllability. For calculating h, it is necessary to accurately determine the upper limit of a change in the variables $\dot{\tau}_m$, ω_d, $s_\tau(\omega_d, \upsilon_L)$ and $D(\omega_d, \upsilon_L)$.

For eliminating the mentioned above deficiencies, it is possible to form h as a function of instantaneous values of the indicated variables:

$$h(t) = K_{h1}|\dot{\tau}_m| + K_{h2}|D_\tau(s_\tau + H_1 C_r\omega_d)\omega_d|,$$

where K_{h1} and K_{h2} are the coefficients of self-tuning of the thruster control system, which satisfy the following inequalities:

$$K_{h1} > \max|(J_d - J_{d0})F_t^{-1}|, \quad K_{h2} > \max|F_m - F_{m0}|.$$

Thus, the control law (8) makes it possible to give to the thrusters described by the system (4) the desired dynamic properties which correspond to equation (5), at any change of their parameters within assigned ranges.

5. SYNTHESIS OF VELOCITY CONTROL SYSTEM

In the second stage of AUV CS synthesis, on the basis of adaptive VSS the AUV velocity CS is synthesized for each degree of freedom. As a CO mathematical model in each AUV velocity control loop we use the equations of form (3) and (5). For the control of this CO we used the following law of control signal τ_d forming at $\upsilon_d \neq 0$ and $\dot{\upsilon}_d = \ddot{\upsilon}_d = 0$:

$$\tau_d = K_{u1}|e|g(s) + K_{u2}\tau, \qquad s = \dot{e} + Ce, \qquad e = \upsilon_d - \upsilon, \tag{15}$$

$$g(s) = \begin{cases} 1, & if\, s > \Delta s \text{ and } \dot{s} > 0 \text{ or } s > -\Delta s \text{ and } \dot{s} < 0 \\ -1, & if\, s < \Delta s \text{ and } \dot{s} > 0 \text{ or } s < -\Delta s \text{ and } \dot{s} < 0 \end{cases},$$

where C is the variable positive coefficient; K_{u1}, K_{u2} are constant positive coefficients, in addition, $K_{u2} = 1/K_d$; K_d is the factor of thruster amplification; $\Delta s > 0$ is the small constant, which is the hysteresis zone size of the switching law.

In the use of the relay control law (15) the imaging point is moved to the beginning of the coordinates of the phase plane, always remaining in the limited zone of high-frequency switching near of the ideal sliding line s=0. The width of this zone is determined by the value Δs. In view of the Δs insignificance, the processes taking place in the VSS, are close to an ideal sliding mode. In this case the behavior of each local AUV velocity control subsystem can be described by the ideal slide equation $\dot{e} + Ce = 0$. Therefore the dynamic properties of the system are determined only by the value of coefficient C and do not depend on the CO variable parameters.

It is obvious that the greater the value of coefficient C, the faster the system error decreases and its accuracy rises. However, to meet the condition for the existence of the sliding mode $s\dot{s} < 0$ [8], the value of coefficient C must always be less than certain value C_{lim}. This value depends on current values of the CO parameters. In traditional VSS, for retaining the switching mode at any CO parameters the C_{lim} value is the lowest. As a result, the operation speed and, consequently, the VSS accuracy always decrease in less loaded modes of CO operation when its parameters allow an increase of C_{lim}.

For increasing the VSS operation speed it is expedient to use the algorithm of self-tuning proposed in work [10]. In these works a continuous tuning (change) of coefficient C is proposed to perform on the basis of indirect estimation of its proximity to the highest value C_{lim} for the current parameters of the system. For the estimation indicated we use the special parameter $\mu = t_g/(t_g + t_s)$ (t_g, t_s are the time intervals of the system motion with different signs of function $g(s)$). Parameter μ always approaches to 1 with the approximation of C to C_{lim}. However, if υ_d changes arbitrarily, the unambiguous dependence between value μ and coefficient C frequently disappears. Researches was performed in work [17] to show that the reason for the disturbance of this dependence during the arbitrary VSS motion is the presence in the dynamics equation of the system of terms determined by signal υ_d and by its derivatives.

So that the adaptive AUV velocity CS should be operational at $\upsilon_d \neq 0$, the value of coefficient K_{u1} must be restricted. These limitations guarantee satisfaction of two conditions simultaneously. The first condition is the falling of the imaging point in the switching zone [8], and the second the existence of the stable mode of high-frequency switching, with any values of the CO parameters. The expressions for the selection of coefficient K_{u1} of regulator (15) take the following form:

$$K_{u1} > \max(K'_{u1}, K''_{u1}), \tag{16}$$

$$K'_{u1} = T_d K_d^{-1} \max|\pm 2d_2 Ce + (Cm - (d_1 \pm 2d_2 \upsilon_d))C + \\ + mK_\mu \Delta\mu + \dot{f}\upsilon/e|,$$

$$K''_{u1} = \max\left((d_1{}^2 T_d)/(4K_d m)\right).$$

The second expression (16) includes a variable value of error *e*. Value *e* in a steady system is always limited both from above and from below. Therefore, value K'_{u1} in the mode of steady high-frequency system switching can always be determined, and it is always limited as well.

However the control law (15) with an arbitrary change of signal υ_d (in the presence of derivatives υ_d) does not ensure stable self-tuning process of coefficient *C*. The steady self-tuning is observed only when a sequence of stepped signals υ_d is given to the input of the velocity loop. As a result, during the system operation the arbitrary continuous signal υ_d must be substituted by a sequence of stepped signals with a certain quantization step value h_{kv}. Value h_{kv} must, on the on one hand, ensure the retention of the coefficient *C* self-tuning, and on another – the sufficiently high accuracy of approximation of the continuous input signal of the velocity loop υ_d.

In work [17] it was proved that to guarantee a steady self-tuning of parameter *C*, parameter h_{kv} must be selected with the help of the expression

$$h_{kv} = 2\Delta s \frac{K_g + K_e}{K_e(K_g - C)} K_\alpha ,$$

where $K_g = \frac{T_d d_1 + m}{2T_d m} + \sqrt{\left(\frac{T_d d_1 + m}{2T_d m}\right)^2 + \frac{K_d K_{u1} - d_1}{T_d m}}$,

$K_e = (d_1(1 - CT_d) - Cm + K_d K_{u1})/CT_d m$, $K_\alpha \le 1.25$ is an additional correction factor.

As a result of applying the developed adaptive regulators (15) and (16), the dynamics of each of the six local AUV velocity control subsystems can be described by elementary linear differential equation with constant coefficients

$$\dot{\upsilon} + \mathrm{C}\upsilon = \mathrm{C}\upsilon_\mathrm{d} . \tag{17}$$

The properties of these subsystems become dependent only on the value of coefficient *C* and they depend on practically no variable AUV parameters.

6. SYNTHESIS OF AUV SPATIAL MOTION CONTROL SYSTEM

In this stage the AUV spatial motion CS will be synthesized. This CS will provide for giving the AUV desired dynamic properties and high dynamic accuracy. As a CO for this CS we consider the AUV velocity control loop developed in the previous synthesis stage. The behavior of this loop as a whole can be described by a matrix differential equation (by analogy with (17)):

$$\dot{\boldsymbol{\upsilon}} + \mathbf{C}\boldsymbol{\upsilon} = \mathbf{C}\boldsymbol{\upsilon}_\mathbf{d} , \tag{18}$$

where $\boldsymbol{\upsilon}_\mathbf{d} = (\upsilon_{d1}, \upsilon_{d2}, \upsilon_{d3}, \upsilon_{d4}, \upsilon_{d5}, \upsilon_{d6})^T \in R^6$ is the vector of AUV desired velocity; $\boldsymbol{C} \in R^{6\times 6}$ is the diagonal matrix of coefficients.

By differentiating equation (2) and after substituting the obtained expression into equation (19), we will obtain:

$$\ddot{\mathbf{x}} = \mathbf{JC}\boldsymbol{\upsilon}_\mathbf{d} - (\dot{\mathbf{J}} - \mathbf{JC})\boldsymbol{\upsilon} . \tag{19}$$

Further we will synthesize the change law υ_d, which will ensure the independence of AUV behavior from the values of matrix elements **J** and $\dot{\mathbf{J}}$. For this purpose, we will write down the equation of the AUV desired motion in the form:

$$\ddot{\mathbf{x}} = \mathbf{K}_\mathrm{p}(\mathbf{x}_\mathrm{d} - \mathbf{x}) + \mathbf{C}(\dot{\mathbf{x}}_\mathrm{d} - \dot{\mathbf{x}}) , \tag{20}$$

where $\mathbf{x_d} = (x_{d1}, x_{d2}, x_{d3}, x_{d4}, x_{d5}, x_{d6})^T \in R^6$ is the vector of AUV desired position; $\boldsymbol{K_p} \in R^{6\times 6}$ is the diagonal matrix of the coefficients which values are selected in accordance with preset parameters of the AUV control quality.

For determining the required control law let us equate the right sides of expressions (19) and (20). Then let us substitute relationship (2) into the obtained equation and let us solve it relative to vector $\boldsymbol{\upsilon}_\mathbf{d}$:

$$\boldsymbol{\upsilon}_\mathrm{d} = (\mathbf{JC})^{-1}(\mathbf{K}'_\mathrm{p}\mathbf{x}_\mathrm{d} - \mathbf{K}_\mathrm{p}\mathbf{x} + \mathbf{C}\dot{\mathbf{x}}_\mathrm{d} - (\mathbf{CJ} + \dot{\mathbf{J}})\boldsymbol{\upsilon}) + \boldsymbol{\upsilon} . \tag{21}$$

It is obvious that to realize the control law (21) it is necessary to calculate the matrix elements $\boldsymbol{(CJ)}^{-1}$ and $\dot{\mathbf{J}}$. This is a serious problem, since matrix elements **J** are complex trigonometric expressions whose values depend on the current values of AUV coordinates. In order to avoid the calculations indicated it is necessary to previously obtain analytical dependences for the elements of these matrices first and then to use these dependences to rapidly calculate the position control law.

7. SIMULATION RESULTS

For the checking of workability and effectiveness of the synthesized control laws we performed a mathematical simulation of different modes of AUV motion. The utilized mathematical model consists of all the six equations of form (1), kinematic relationships of form (2), plus six systems of equations of form (4), which describe the complete dynamics of all AUV thrusters.

The mathematical simulation was conducted with the following AUV parameters and synthesized regulators: F_{mmin} = 0.065 N·s^2; F_{mmax} = 0.085 N·s^2; F_τ = 4N·s^2/m; H = 0.12 m; δH = 0.002 m; C_r = 0.12; A_s = 0.01m^2; C_m = 0.002; C_f = 0.001; C_ω = 0.01; k_w = 0.5 N·m/V; k_m = 0.5 N·m/A; R = 2 Ohm; J_{dmin} = 0.01 kg·m^2; J_{dmax} = 0.02 kg·m^2; k_y = 20; J_{d0} = 0.01 kg·m^2; F_{m0} = 0.075 N·s ^{2}; K_{h1} = 0.01; K_{h2} = 0.01; m_a = 1300 kg; J_{xx} = 900 kg·m^2; J_{yy} = 700 kg·m^2; J_{zz} = 850 kg·m^2; Y_c = 0.03 m; B = 150 kg; λ_{ijmin} = 150 kg (i, j = =1..3); λ_{ijmax} = 1200 kg (i, j = 1..3); λ_{ijmin} = 70 kg·m^2 (i, j = 1..3); λ_{ijmax} = 900 kg·m^2 (i, j = 1..3); d_{1imin} = 100 kg·s^{-1}; d_{1imax} = 200 kg·s^{-1}; d_{Mmin} = kg·m^{-2}; d_{Mmax} = kg·m^{-2};

T_d = 0.1 s; C_{min} = 3; K_{u1} = 100; ξ = 0.25; μ_{max} = 0.9; k_s = 12; h_{kv} = 0.05 m/s; Δs = 0.01. The simulation was carried out with the help of solution of ordinary differential equations by the Runge-Kutta method.

For the comparison, in the AUV control, we also used the traditional linear system, which consists of 4 uniform regulators controlling the yaw φ, the pitch ψ, and also linear x and y coordinates [18]. Each of these four systems (for example, for the control of x coordinate) takes the form:

$$\tau_{dx} = k_{x1}(x_d - x) + k_{x2}\dot{x}, \quad (22)$$

where τ_{dx} is the desired thrust value along axis x; k_{x1}, k_{x2} are the positive coefficients.

This control system was investigated with two versions of tuning its parameters. The first version of the tuning was produced taking into account that the regulators would ensure the aperiodic nature of the system reaction to the stepwise input signal with minimal transit time. With the second version, in the steady mode, during the performance of periodical sinusoidal input signal, the same temporal delay (phase displacement) as in the synthesized self-tuning system was ensured.

Figure 2 shows the results of the investigation of the CS synthesized in this article, which contains internal thruster CS (8) and velocity CS (15), (16) and also the position controller (21), at feeding a stepwise demand signal. Curve 1 corresponds to the process of changing the AUV position error with the "best", while curve 2 – with the "worst" values of the AUV parameters. For the comparison, Fig. 2 also gives the processes of changing the AUV position error during the use of a traditional linear CS of form (22) (first version of tuning) with the "best" (curve 3) and "worst" (curve 4) values of the AUV parameters.

Figure 2 shows that a traditional linear CS with constant coefficients makes it possible to attain the acceptable control quality only with the "best" values of the AUV parameters.

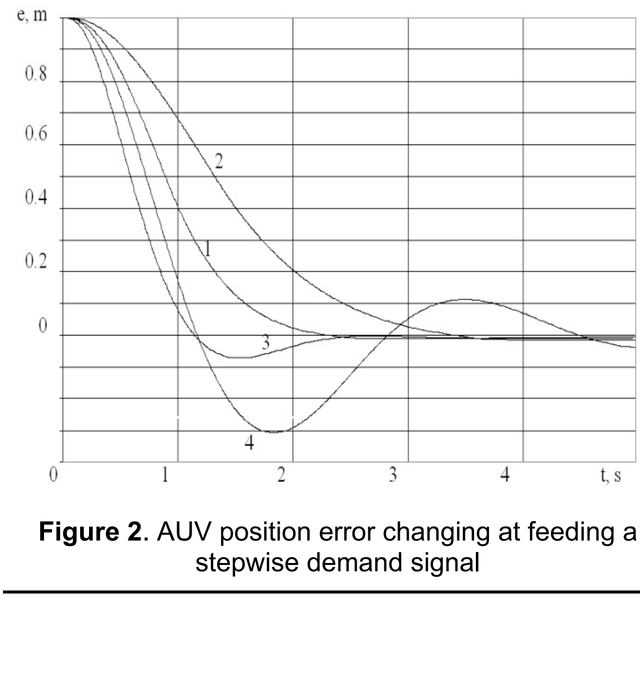

Figure 2. AUV position error changing at feeding a stepwise demand signal

At the "worst" values of these parameters, significant worsening in the control quality is observed (the transit time grows by 2.5 times and the overregulation increases more than three times). However, the application of an adaptive AUV CS makes it possible not only to avoid overregulation, but also, under favorable working conditions, to increase the system operation speed by almost 1.5 times. Under unfavorable conditions for the AUV work in comparison with CS of form (22) this operation speed increases almost two times.

Figures 3a and 3b show the processes of changing the parameter μ and coefficient C. In these figures number 1 designates the processes in CS with the "best" values, and number 2 - with the "worst" values of the AUV parameters.

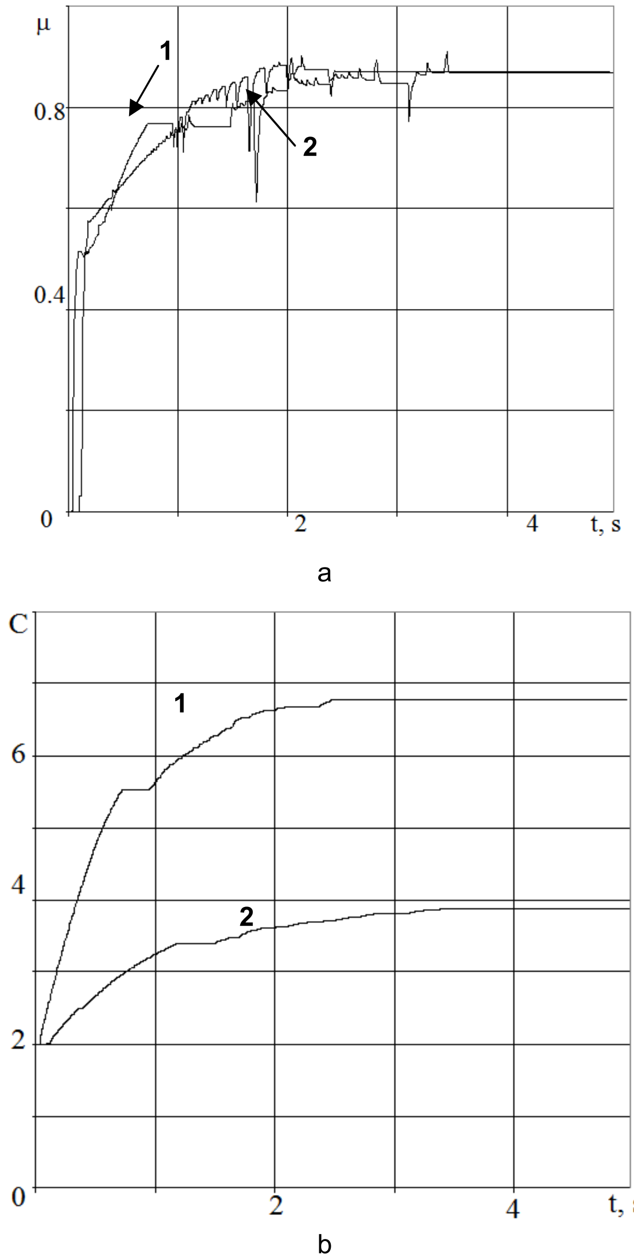

Figure 3. Changes in the parameter μ and coefficient C with the stepwise input signal

As can be seen from Figures 3a and 3b, at the self-tuning of the CS, parameter μ reaches its highest predetermined constant value, while coefficient C is tuned to different values depending on the current values of the AUV parameters. It means that in the case of applying the control law (15), (16) it is possible to restore the unique dependence between the parameter value μ and coefficient C in the forced mode of the AUV motion.

The synthesized control system was also investigated in the AUV motion mode along a complex three-dimensional trajectory. The form and parameters of the trajectory in the projection on the vertical plane are given in Figure 4. The investigation of this AUV motion mode was conducted with the following values of the velocity υ_x: $\upsilon_{xb} = 0.7$ m/s, $\upsilon_{xab} = 0.55$ m/s, $\upsilon_{xbc} = 0.8$ m/s, $\upsilon_{xc} = 1$ m/s.

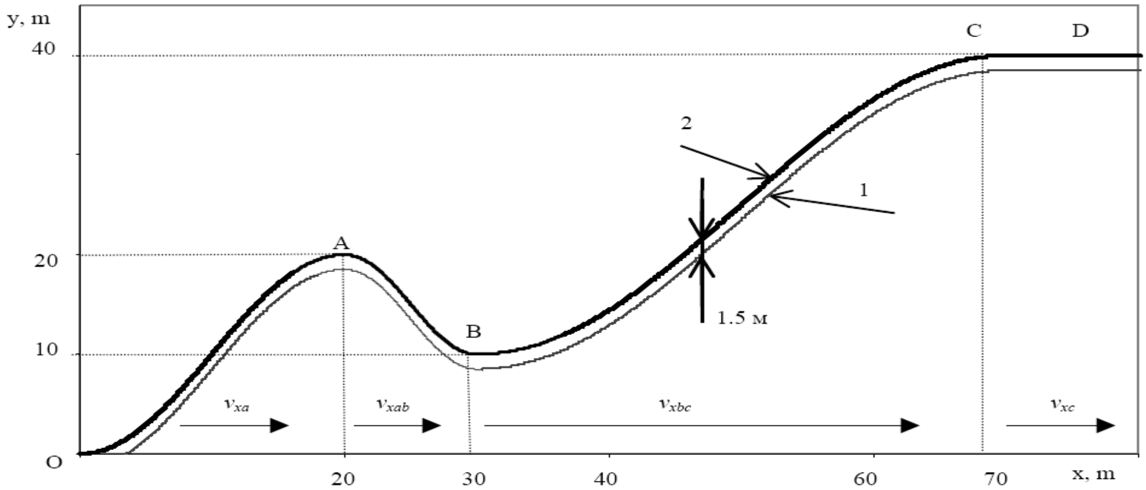

Figure 4. Desired trajectory of the AUV motion

On the Figure 4 the curve 1 is a surface profile, and curve 2 is the desirable trajectory of moving along this surface.

Figure 5 shows the results of the simulation of AUV motion on a trajectory (see figure 4) with the use of different CS. The broken line corresponds to AUV motion with the use of linear regulators (22), while the solid line – with the use of a synthesized adaptive CS. The broken-point curve corresponds to the program (desirable) process of changing the coordinates.

As the results of simulation showed, the traditional linear CS of form (22) does not make it possible to ensure good control quality during the AUV motion along complex three-dimensional trajectories with relatively high speed (deviation from the desirable trajectory can reach 5-10 m).

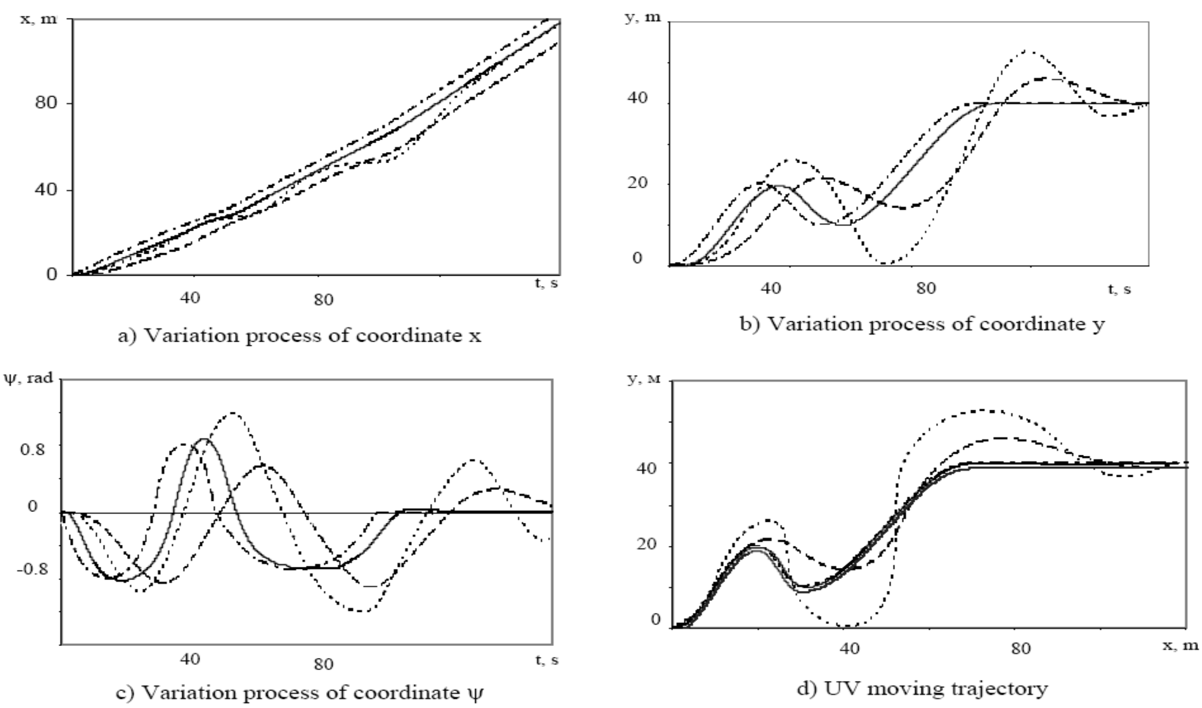

Figure 5. Processes of changes of the coordinates and trajectory of AUV motion

In this case, the CS synthesized on the basis of the method proposed in this article, ensures sufficiently precise AUV motion (deviation from the trajectory does not exceed 0.6 m).

8. CONCLUSIONS

This article proposes a unified method of AUV spatial motion control system synthesis, which consists of three loops: the thruster control loop, velocity control loop, and also the control loop of position and orientation. The CS for thrusters was synthesized on the basis of their most precise dynamic model, which made it possible to give them desired dynamic properties in any operating modes. The AUV velocity CS is built on the basis of an adaptive VSS so as to provide for the self-tuning of the high-frequency switching zone position with forced AUV motion without any identification of their current parameters. This made it possible to considerably increase the operating speed of the VSS in favorable modes of the AUV operation. The synthesized external control loop of the AUV position and orientation, taking into account high-quality internal loops made it possible to obtain high resulting dynamic accuracy of the AUV control as a whole.

The mathematical simulation of the synthesized multilevel CS in different AUV motion modes confirmed its fitness for work, accuracy and high effectiveness in comparison with traditional regulators adapted for the AUV control.

9. ACKNOWLEDGEMENTS

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Metod sinteze kontrolnog sistema za prostorno kretanje autonomnog podvodnog vozila

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Apstrakt

Rad se bavi sintezom kontrolnog sistema za prostorno kretanje samostalnog podvodnog vozila na osnovu principa dekompozicije. Ceo kontrolni sistem je podeljen na šest kontrolnih podsistema sa posebnim stepenom slobode. S druge strane, svaki podsistem sadrži tri kontrolne petlje: pogonska kontrolna petlja, kontrolna petlja brzine vozila i kontrolna petlja pozicije vozila. Rad predlaže različite metode sinteze kontrolora za svaku petlju. Matematička simulacija potvrđuje da je izabrana strategija sinteze dobra i pokazuje visoku efikasnost dobijenog kontrolnog sistema.

Ključne reči: *podvodno vozilo; kontrolni sistem; adaptivni sistem; samohodni; klizni režim*