Control System Design for Autonomous Underwater Vehicle

Pshikhopov V.Kh., Medvedev M.Yu., Gaiduk A.R., Gurenko B.V.
Department of Electric Science and Mechatronics
Southern Federal University
Taganrog, Russia
e-mail: pshichop@rambler.ru, medvmihal@gmail.com, gaiduk_2003@mail.ru, boris.gurenko@gmail.com

***Abstract*— This paper presents adaptive control system for the autonomous underwater vehicle. A nonlinear interrelated dynamic model of the underwater vehicle is considered. The novelty of developed control system is in use of positional-trajectory control method. This means feasibility of Autonomous Underwater Vehicle in complicated trajectories with relatively small computational resources. Adaptation of the control system is based on robust disturbances estimation. Modeling results validate proposed methods.**

Keywords-component; adaptive control, estimations, underwater vehicle

I. INTRODUCTION

Development of AUV able for complicated missions requires development of novel control algorithms for closed loop system [1,2]. Additional complexity in the control of underwater vehicles rises from undetermined external environment, constraints of navigation systems and the complexity of the mathematical models of underwater vehicles. In the general case for control design of underwater vehicles are used search less adaptive and robust control systems. This paper presents new method of adaptive control systems design on base of position-trajectory control method [3, 4].

II. MATHEMATICAL MODEL

Coordinate system presented in Fig.1 is used in the mathematical model of the underwater vehicle. The base system $O^0X^0Y^0Z^0$ is a fixed external coordinate system. The origin of body system OXYZ located in the center of the application of the buoyancy force acting on the underwater vehicle.

Mathematical model of the kinematics of the AUV links linear and angular velocities in the base and body coordinate systems:

$$\begin{bmatrix} \dot{r}_0 \\ \dot{\Theta} \end{bmatrix} = \begin{bmatrix} A^T & 0 \\ 0 & A_\omega \end{bmatrix} \begin{bmatrix} V \\ \omega \end{bmatrix} \quad (1)$$

r_0 – vector of linear coordinates of AUV in the base coordinate system; Θ – vector of the Euler angles; V, ω – vectors of linear and angular velocities of the AUV in the body coordinate system; A^T, A_ω – matrixes of kinematic transformation [3, 4].

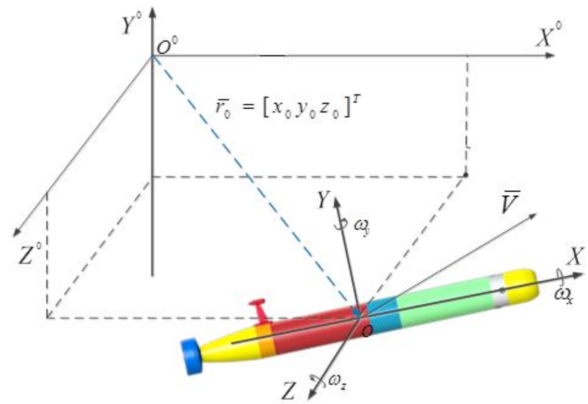

Fig. 1. Coordinate system of underwater vehicle

A vector $Y = [r_0^T \quad \Theta^T]^T$ is a vector of external coordinates, and the vector $X = [V^T \quad \omega^T]^T$ - vector of internal coordinates.

The dynamic equations of AUV for constant mass are:

$$\begin{bmatrix} \dot{V} \\ \dot{\omega} \end{bmatrix} = M^{-1} \begin{bmatrix} F \\ N \end{bmatrix} \quad (2)$$

M – matrix of mass and inertia parameters; F, N – resulting vector of forces and moments acting on the AUV [3, 4]:

$$F = G + A_S + P_D + R_H \quad (3)$$

$$N = N_G + N_D + N_H \quad (4)$$

G and N_G – vector and moment of gravity forces; A_S –main vector of buoyancy force; P_D and N_D – vector and moment of thrust produced by propellers of AUV; R_H and N_H – vector and moment of the hydrodynamic forces acting on the body and tail of AUV.

The dynamics of the actuators AUV is described as

$$T\dot{\delta} + \delta = K\,U \quad (5)$$

978-0-7695-5139-5/13 $26.00 © 2013 IEEE
DOI 10.1109/.21

δ – vector of thrust propellers and rudders influence; T , K – matrix of time constants and coefficients of transmission; U – control.

Propulsion and steering system (PSS) under consideration of AUV includes two main propulsion drives, six thrusters, vertical and horizontal rudders. Each propulsion drive is given propeller driven by the motor. The thrust created by propulsion propeller depends on the velocity of motion of AUV and diving depth (density of water).

This PSS includes two horizontal thrusters, which are mounted in two horizontal channels at different distances from the lateral plane of symmetry and below the horizontal plane which crosses the center of the body of the AUV. The PSS includes four vertical thrusters located in four vertical channels. These thrusters are also mounted at different distances from the lateral plane of symmetry, but symmetrically to the longitudinal vertical plane of symmetry.

Thrusters creates a thrust directed along the appropriate axis of the channel in which it is located. The direction of thrust is considered positive if its direction coincides with the direction of the axis of the body coordinate system, parallel to which distribution channel put the corresponding thrusters or axis of rotation of the propeller. Otherwise a thrust is negative. The point of application of the tractive force P_{H1} and P_{H2} horizontal thrusters are shown in Fig. 2 characters TD_{H1} and TD_{H2}. Similarly, the point of application of the tractive force P_{Vi}, vertical thrusters are shown in Fig. 3 characters P_{Vi},. Fig. 3 characters TD_{V1} and $TD2_{V2}$ are designated as the point of application of the tractive force of both propellers AUV.

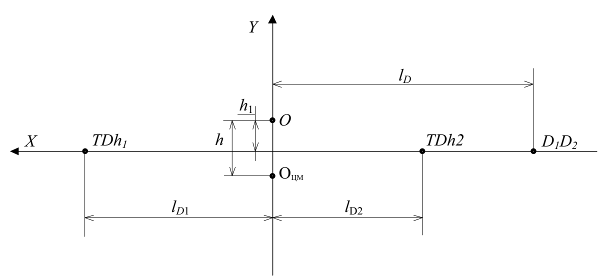

Figure 2. The point of force application of horizontal thrusters

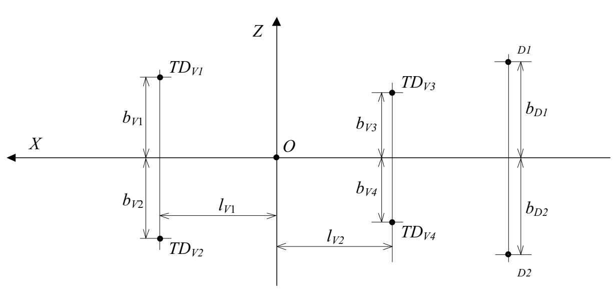

Figure 3. The point of force application of vertical thrusters

Horizontal part of rudders includes two surfaces synchronously rotating in angle $\pm 35^{\circ}$ at a rate ± 7 deg/s. Vertical part of rudders is one surface rotating in one and the same angle $\pm 35^{\circ}$ at a rate within ± 7 deg/s.

Projections of total thrust vector P_D of propulsion drives D_1 and D_2 in the body coordinate system OXYZ is determined by the following expressions:

$$P_{Dx} = P_1 + P_2 ,\; P_{Dy} = 0 ,\; P_{Dz} = 0 , \qquad (6)$$

Moment generated by propulsion D_1 and D_2 in the body coordinate system OXYZ has the projections:

$$N_{Dx} = P_1 + P_2 , N_{Dy} = \left(P_1 - P_2\right) b_{D1} ,\; N_{Dz} = \left(P_1 + P_2\right) h_1 , \qquad (7)$$

The projections of the moments of forces generated by horizontal thrusters, are:

$$P_{Hx} = 0 ,\; P_{Hy} = 0 ,\; P_{Hz} = P_{H1} + P_{H2} , \qquad (8)$$

$$N_{Hx} = \left(P_{H1} + P_{H2}\right) h_1 \; N_{Dy} = -P_{H1} l_{H1} - P_{H2} l_{H2} \; N_{Hz} = 0 \qquad (9)$$

The projections of the moments of forces generated by vertical thrusters, are:

$$P_{Vx} = 0 ,\; P_{Vy} = \sum_{i=1}^{4} P_{Vi} ,\; P_{Vz} = 0 , \qquad (10)$$

$$N_{Vx} = \left(P_{V2} - P_{V1}\right) b_{V1} + \left(P_{V4} - P_{V3}\right) b_{V3} ,\; N_{Vy} = 0 , \qquad (11)$$

$$N_{Vz} = \left(P_{V2} + P_{V1}\right) l_{V1} - \left(P_{V4} + P_{V3}\right) l_{V3} , \qquad (12)$$

The forces and moments generated by the rudders are the hydrodynamic and only occur when AUV is moving. These forces and moments depend in complex ways on the rudder angle as the control mechanism, on the speed of the AUV, its angle of attack, drift, roll and pitch. In this regard, they are determined by CFD researches. For example, dependencies of projection of torque and forces produced by the horizontal depth rudder on the axis of body coordinate system with a speed of 8 m/s and a zero angle of attack and drift are shown in Fig.4. As we can see, moment N_H and the thrust P_H are non-linearly dependent on the angle of the depth rudders. Based on these studies we can conclude that at low angles most of the nonlinear characteristics accurately approximated by linear functions. In the general case there rudders forces and moments having nonzero projection onto all three axes when rudders angles change. Projections of moments and forces created by rudders on some axis for small rudder angles are small, so they are often assumed to be zero. Thus, the vectors of control forces and moments generated by PSS of the AUV, are:

$$P_{con}(\delta) = \begin{bmatrix} P_{Dx} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ P_{Hz} \end{bmatrix} + \begin{bmatrix} 0 \\ P_{Vy} \\ 0 \end{bmatrix} + \begin{bmatrix} P_{Hx} \\ P_{Hy} \\ P_{Hz} \end{bmatrix} + \begin{bmatrix} P_{Vx} \\ P_{Vy} \\ P_{Vz} \end{bmatrix} , \qquad (13)$$

$$N_{con}(\delta) = \begin{bmatrix} 0 \\ N_{Dy} \\ N_{Dz} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ N_{Hz} \end{bmatrix} + \begin{bmatrix} 0 \\ N_{Vy} \\ 0 \end{bmatrix} + \begin{bmatrix} N_{Hx} \\ N_{Hy} \\ N_{Hz} \end{bmatrix} + \begin{bmatrix} N_{Vx} \\ N_{Vy} \\ N_{Vz} \end{bmatrix} , \qquad (14)$$

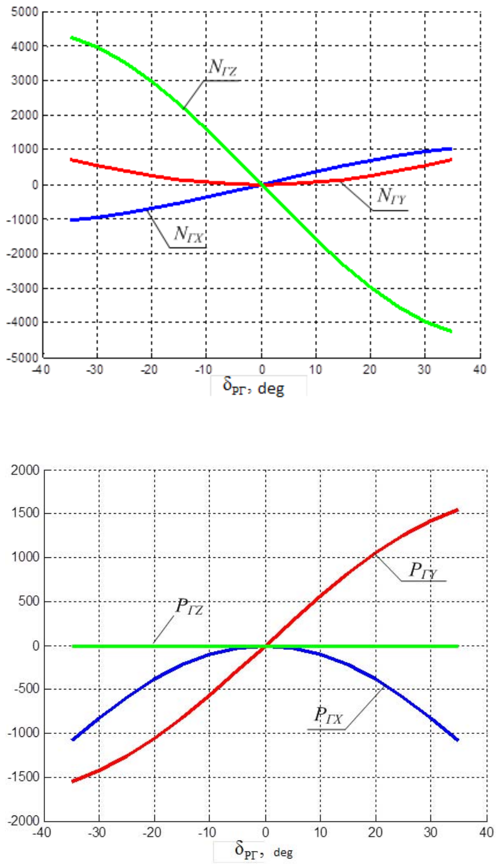

Figure 4. – Projection of force and torque generated by the horizontal rudders

Thus, the vector δ is a five-dimensional vector of controls. Each of these controls determines the value of the force and torque, which is generating by the corresponding element of PSS: propellers, horizontal and vertical thrusters, horizontal and vertical rudders. The values δ_i generated by the AUV control system enters to the input of the corresponding actuators.

During the identification of a mathematical model of AUV, the following parameters are determined: mass m, position of the center of mass $r_{\text{т}}$, inertia tensor $\{J_{i,k}\}$, added mass matrix $\{\lambda_{m,n}\}$; hydrodynamic coefficients $c_x, c_y, c_z, m_x, m_r, m_z$.

Position of the center of mass $r_{\text{т}}(y_0)$ and inertia tensor $\{J_{i,k}(y_0)\}$ of AUV calculated in SolidWorks software. The calculation results are placed in the arrays used in the control algorithms AUV. The calculation of added mass is done by empirical relationships in the approximation of an ellipsoid shape of AUV according to its dimensions.

To calculate the hydrodynamic characteristics of the AUV used CFD software FineHexa (NUMECA International), STAR CD.

Results of CFD researches for the considered AUV are presented in Fig. 5, 6 and 7.

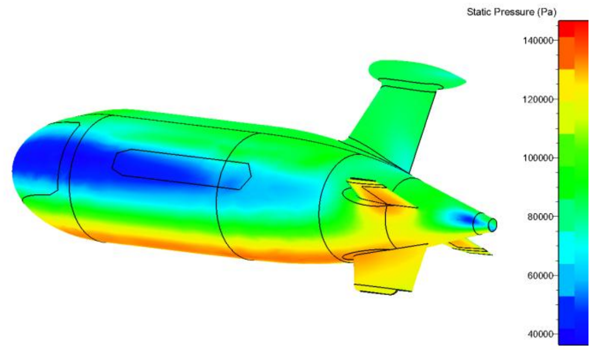

Figure 5. – The pressure distribution on the body AUV

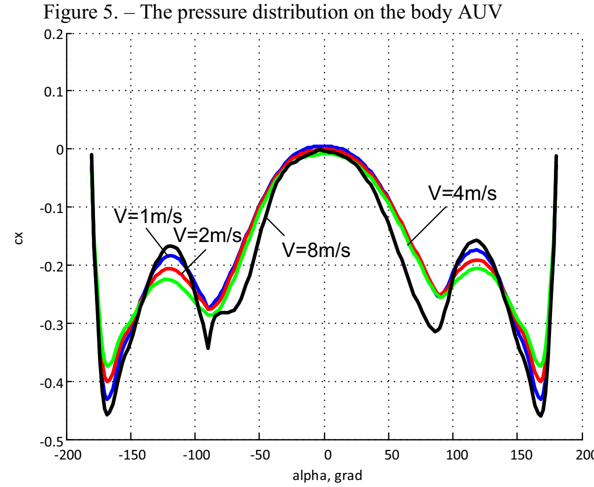

Figure 6. – Dependence of the coefficient c_x from angle of attack at different velocities of AUV

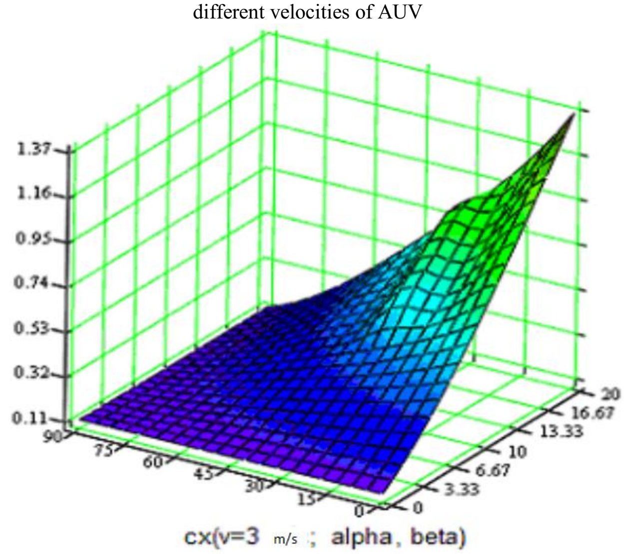

Figure 7. – Dependence of the coefficient cx from angles of attack(alpha) and angles of drift(beta)

The coefficients of the hydrodynamic forces and moments are calculated as a function of the angle of attack, drift, velocity and the angular rate of the AUV. Full results of the hydrodynamic calculations of the coefficients are described in the tables that are used in the research process and motion control of AUV.

The density of seawater as a function of salinity, temperature, and pressure is determined by the expression [5]

$$\rho(S,t^\circ,p_{\text{в}})=\frac{\rho(S,t^\circ,0)}{1-p_{\text{в}}K^{-1}(S,t^\circ,p_{\text{в}})}, \tag{15}$$

ρ – the density of sea water,kg/m^3; S – Practical salinity of the sea water; $p_{\text{в}}$ – hydrostatic pressure; $\rho(S,t^\circ,0)$ – the density of sea water at a pressure of standard atmosphere (101325 Pa); $K(S,t^\circ,p_{\text{в}})$ – average modulus seawater defined by the expression given, for example, [6].

Seawater pressure $p_{\text{в}}(H)$ change with changing depth H ,m, according to [5], is determined by

$$p_{\text{в}}(H)=p_{\text{a}}+\gamma_{\text{в}}H, \tag{16}$$

$p_a=101325$ – atmospheric pressure, Pa; $\gamma_{\text{в}}$ – the specific weight of sea water, $\gamma_B=9813$ Н/м³.

The most significant factors influencing on the density of sea water is the hydrostatic pressure and temperature. In particular, this indicates borrowed from [6] plots of the density of the seawater pressure $P=p_{\text{в}}-101325$ Pa at the salinity $S=35\,0/00$ and at various temperatures shown in Fig. 8.

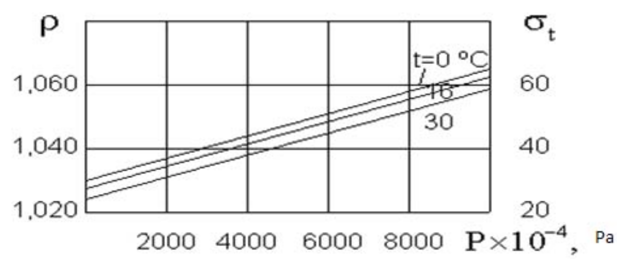

Figure 8. Density dependence of the pressure and temperature

Hence for practical calculations, we can take the linear dependence of the density of sea water from the depth and temperature and the effect of changes in salinity attributed to external disturbances of low intensity. Then the dependence of the density of sea water on the depth and temperature will be determined by the following expression

$$\rho(H,t^\circ)=1039{,}6-0{,}241t^\circ+0{,}00478H, \tag{17}$$

H – depth in m; t° – water temperature in degrees of Celsius.

Change in the buoyancy caused by the change in the density of sea water and compressing the body of the apparatus by hydrostatic pressure, can be compensated by changing the mass of water in the ballast tanks or mass of buoyancy blocks. In submarines, the ability to control buoyancy, often used to change the depth of the dive.

When driving the AUV at different depths in the water, buoyancy changes, taking both positive and negative values. The reason for this is changing of the density of water and compressing the body of the apparatus by hydrostatic pressure.

Commonly in practice, the requirement is stated that the AUV vehicle must have positive buoyancy when operating at a given depth and on the surface of water. From this we can conclude that the buoyancy blocks of the AUV have a constant mass. Therefore, when the AUV dives, buoyancy changes in some fixed acceptable range, that does not affect the performance of AUV.

III. CONTROL SYSTEM DESIGN

Synthesis of motion control algorithms carried out on the basis of the position-trajectory control of moving objects [3,4]. The time constant is much smaller than the time constants of the AUV. This allows the equation does not include engines in the primary loop motion control and control system synthesized by equations (1) and (2). AUV motion control algorithm is as follows:

$$\begin{aligned}F_{\text{u}}&=-F-\hat{F}_v-M\left(\left(2A_1Y_m+A_2\right)R+A_4\right)^{-1}\times\\&\times\left(2A_1\dot{Y}_mRX+\left(2A_1Y_m+A_2\right)\dot{R}X+T_1\psi_{\text{TP}}+T_2\psi_\Sigma\right)\end{aligned} \tag{18}$$

$Y=\begin{bmatrix}x_0 & y_0 & z_0 & \psi & \vartheta & \gamma\end{bmatrix}^T$ – position vector of the AUV in the base coordinate system; $Y_m=diag\left(\begin{bmatrix}x_0 & y_0 & z_0 & \psi & \vartheta & \gamma\end{bmatrix}^T\right)$ – diagonal matrix; A_1,A_2,A_3 – matrix and vector coefficients which determine the trajectory of the AUV; ψ_{TP} – vector trajectory errors; T_1,T_2 – matrix of constant coefficients; $X=\begin{bmatrix}V_x & V_y & V_z & \omega_x & \omega_y & \omega_z\end{bmatrix}^T$ – AUV velocity vector in body coordinate system; A_4,A_5 – matrix and vector defining the required speed AUV; ψ_Σ – generalized error of control system; F – vector of dynamic and external forces and moments acting on the AUV; $\dot{Y}_m=diag\left(RX\right)$ – diagonal matrix; $\dot{R}$ – matrix of derivatives of the elements of the matrix R ; $\hat{F}_v$ – vector of disturbances estimations.

The equations of robust disturbance estimator are [7]:

$$-\dot{\hat{z}}=-L\hat{z}-\left(G_1+L\right)C^{-1}\begin{bmatrix}F+F_{con}\\N+N_{con}\end{bmatrix}-L^2M\begin{bmatrix}V\\\omega\end{bmatrix}, \tag{19}$$

$$\widehat{F}_v = \hat{z} + LM\begin{bmatrix} V \\ \omega \end{bmatrix}, \tag{20}$$

$$G_1 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \dots & & & & \dots & & & & \dots & & & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{21}$$

$$L = \begin{bmatrix} 0 & 1 & 0 & 0 & 0\,0\,0\,0\,0\,0 & 0 & 0 \\ -l_{21} & -l_{22} & 0 & 0 & 0\,0\,0\,0\,0\,0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0\,0\,0\,0\,0\,0 & 0 & 0 \\ 0 & 0 & -l_{34} & -l_{44} & 0\,0\,0\,0\,0\,0 & 0 & 0 \\ \dots & & & & \dots & & \dots \\ 0 & 0 & 0 & 0 & 0\,0\,0\,0\,0\,0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0\,0\,0\,0\,0\,0 & -l_{1211} & -l_{1212} \end{bmatrix}$$

IV. AUV AUTOPILOT SIMULATOR

Fig. 9 shows the structure of the AUV control systems simulator.

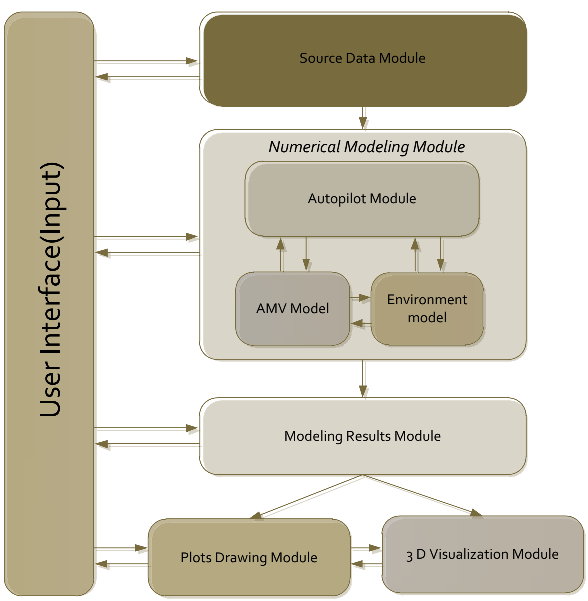

Figure 9. The structure of the AUV control systems simulator

The simulator consists of a user interface, database, computer module and visualization modules. The system allows research the stability, quality of AUV control, as well as to model the various modes of motion of AUV.

Consider the example of the synthesis of a trajectory controller that performs the task motion along the trajectories with a given speed of 2 m/s from point A_0 to point A_f. The value of functional matrices in the controller (2, 3) in the case of path following tasks:

$$\psi_{mp} = \begin{bmatrix} \psi - \arctan\left(A_1 Y^T Y + A_2 Y + A_3\right) - \\ - \arctan\left(V_z, V_x\right) \\ \upsilon - k_1\left(y_0 - y^*\right) - \alpha^* \\ \gamma \\ \end{bmatrix}, \tag{22}$$

$$\psi_{c\kappa} = \begin{bmatrix} V_x - V^* \\ -\mathrm{V}\sin\left(\alpha^*\right)\cos\left(\beta\right) \end{bmatrix}, \tag{23}$$

y^* - given depth of functioning; α^* - optimum angle of attack, providing a minimal pitching moment AUV; k_1 - coefficient of settings; V^* - given velocity of the AUV.

The control algorithm (18) is augmented by constraints for the maximum and minimum pitch angles by inequalities. Also control algorithm automatically limits the speed of the AUV relative to the environment and the angular rates of the AUV. If the AUV is in a situation when the angles greater than the maximum allowed, the control system stops the execution of the task and stabilizes the device in a mode of drift along the flow. After that, the resumption of the task is occurred. Robust control algorithms proposed in [7, 8] are used in stabilizing of the AUV.

Results of simulation of control system shown in Fig.10 and Fig/11.

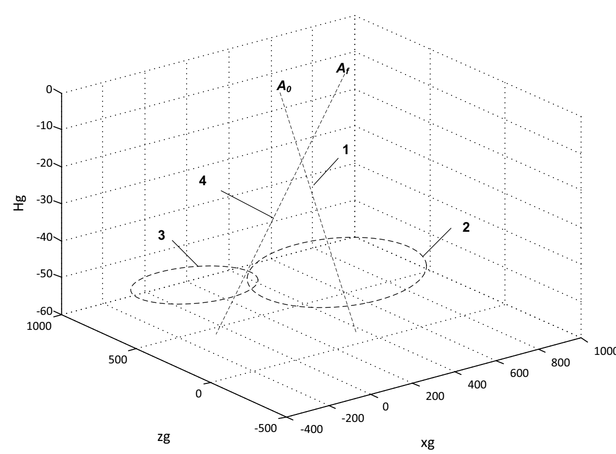

Figure 10. Specified trajectory

One of the advantages of the used controller is a simple change of trajectory. To set the desired trajectory just enough to change the parameters of the quadratic form.

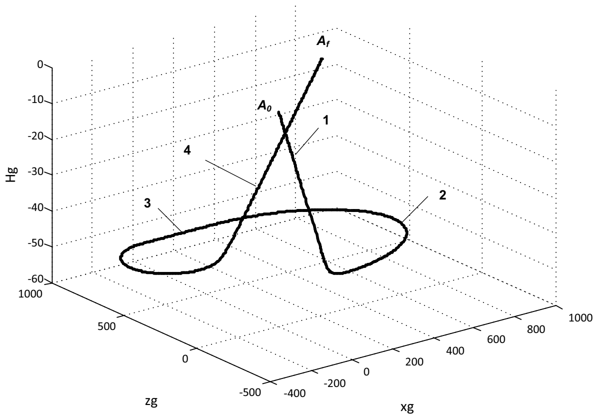

Figure 11. The trajectory of the AUV

In the first segment the AUV performs a dive on a sloping straight line, the value of the coefficients of quadratic forms in (2) are:

$$A_{11} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix}, A_{12} = \begin{vmatrix} 1 & 5 & 0 \end{vmatrix}, A_{13} = 0,$$

$$A_{21} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix}, A_{22} = \begin{vmatrix} 0 & 0 & 1 \end{vmatrix}, A_{23} = 0$$

,

In the second portion the AUV is moving in an arc of an ellipse defined by the equation

$$\frac{(x-x_0)^2}{r_x^2} + \frac{(z-z_0)^2}{r_z^2} = 1,$$

$x_0 = 250, z_0 = 400$ - coordinates of the center, $r_x = 600, r_z = 400$- axis of the ellipse, at a depth of 50 meters. Accordingly, when performing this motion, value of the coefficients of quadratic forms are:

$$A_{11} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix}, A_{12} = \begin{vmatrix} 0 & 1 & 0 \end{vmatrix}, A_{13} = 50,$$

$$A_{21} = \begin{vmatrix} 1/r_x^2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/r_z^2 \end{vmatrix}, A_{22} = \begin{vmatrix} -2\,{}^{x_0}\!/_{r_x^2} & 0 & -2\,{}^{z_0}\!/_{r_z^2} \end{vmatrix}, A_{23} = {}^{x_0^2}\!/_{r_x^2} + {}^{z_0^2}\!/_{r_z^2} - 1$$

,

In the third section the AUV is moving along the arc of a circle given by the equation

$$(x-x_0)^2 + (z-z_0)^2 = R_0^2,$$

$x_0 = -100, z_0 = 600$ - coordinates of the center, $R_0 = 200$ - radius. Depth is 50 m. The coefficients of the quadratic form are:

$$A_{11} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{vmatrix}, A_{12} = \begin{vmatrix} 0 & 1 & 0 \end{vmatrix}, A_{13} = -900,$$

$$A_{21} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{vmatrix}, A_{22} = \begin{vmatrix} -2x_0 & 0 & -2z_0 \end{vmatrix}, A_{23} = x_0^2 + z_0^2 - R_0^2$$

,

After doing the above maneuvers AUV moves on a sloping line in the defined point, this maneuver in the graphs corresponds to the fourth section in figure 11.

The obtained simulation results confirm the efficiency and correctness of the proposed algorithms.

V. CONCLUSION

Developed control system moves AUV with no separation of his movements on the longitudinal and lateral component and without linearization of the model. The report presents the basic control algorithms. The breaking down of the control forces and moments in the control actuators is performed by means of the synchronization of tilt angles and thrusts of steering systems.

The control algorithm (18-21) carries the ideology of the movement apparatus nose ahead. If the actuators of the AUV allow implementation of reverse or lateral movement, the control algorithms change.

ACKNOWLEDGMENT

This paper was supported by Russian Federation Grants VSh-1557.2012.10, MD-1098-2013.10, and RFFI 13-08-00315.

REFERENCES

[1] Healey, Anthony J., Lienard, David. Multivariable sliding mode control for autonomous diving and steering of unmanned underwater vehicles // IEEE Journal of Oceanic Engineering. 18 (3). 1993. Pp. 327-339

[2] Stilwell, D.J., Bishop, B.E. Platoons of underwater vehicles // IEEE Control Systems Magazine 20 (6). 2000. Pp. 45-52.

[3] Pshikhopov V.Kh., Medvedev M. Y., Sirotenko M.Y., Kostjukov V.A. Control System Design for Robotic Airship // Preprints of the 9-th IFAC Symposium on Robot Control. Gifu, Japan. September 9 – 12, 2009. Pp. 123 – 128.

[4] Pshikhopov V., Medvedev M., Kostjukov V., Fedorenko R., Gurenko B., Krukhmalev V. Airship autopilot design // Proceedings of SAE AeroTech Congress&Exibition. October 18-21, 2011.

[5] Зори А.А., Корнеев В.Д., Хламов М.Г. Методы, средства, системы измерения и контроля параметров водных средств. Донецк: РИА ДонГТУ, 2000. 388 с

[6] http://www.masters.donntu.edu.ua/2001/kita/vavitch/diss/lib/zori.htm

[7] Medvedev M. Y., Pshikhopov V.Kh., Robust control of nonlinear dynamic systems // Proc. of 2010 IEEE Latin-American Conference on Communications. September 14 – 17, 2010, Bogota, Colombia. ISBN: 978-1-4244-7172-0.

[8] Pshikhopov V.Kh., Medvedev M.Yu. Block Design of Robust Control Systems by Direct Lyapunov Method // Preprints of the 18th IFAC World Congress. August 28 – September 2, 2011. Milano, Italy.