DOI: 10.2507/31st.daaam.proceedings.xxx

SYSTEM OF HIGH-PRECISION MOVEMENTS CONTROL OF UNDERWATER MANIPULATOR

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This Publication has to be referred as: Filaretov, V[ladimir]; Konoplin, A[lexander]; Zuev, A[lexander] & Krasavin, N[ikita] (2020). System of High-precision Movements Control of Underwater Manipulator, Proceedings of the 31st DAAAM International Symposium, pp.xxxx-xxxx, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/31st.daaam.proceedings.xxx

Abstract

The paper deals with system of high-precision movements control of underwater manipulator mounted on underwater vehicle. Described control system allows to compensate negative torques in joints of the manipulator which appear due to high-speed movements of underwater manipulator in fluid environment, and also compensate coulomb friction and viscous friction moments in link electric drive units. This task is achieved due to using of self-adjusting corrective devices of manipulator electric drive units. Because of recurrent algorithm for solving the inverse problem of dynamics doesn't allow to accurately determine effects of a viscous friction influence on manipulator's moving links, here is suggested to use observers to determine and then take into account unaccounted moments for each manipulator electric drive unit. Numerical simulation of synthesized 3-dof underwater manipulator control system was performed. It showed that described system significantly improves dynamic accuracy of high-speed movements of manipulator gripper during various technological operations.

Keywords: underwater multilink manipulator; underwater vehicle; identification; high-precision; observer.

1. Introduction

The solution to the problem of high-precision control of multilink manipulators (MM) mounted on underwater vehicles is necessary to expand the scope of application of underwater robotics when performing specific work operations [1], [2]. This problem is caused by the fact that the moving parts of the MM are exposed to significant and difficult to determine dynamic effects from the surrounding water environment [3], [4], which change the parameters of control objects. This significantly reduces the accuracy of moving working tools during manipulation work.

At present, a recurrent algorithm [3] for solving the inverse problem of dynamics is known. It allows in real-time to calculate interactions between the degrees of mobility of underwater MM and other external influences from a viscous fluid. However, the accuracy of the analytical calculation of these interactions and impacts is low due to the great complexity of accurate a priori determination of the parameters of the effects of a viscous fluid on all MM links [5] and the values of the liquid masses attached to these links. At the same time, MM often move underwater objects with a priori unknown parameters. In addition, during the operation of underwater MM, there may be an unexpected increase of the moments of viscous and coulomb friction in the electric drive units (due to changes of the properties and contamination of the lubricant, friction in the sealing connectors, etc.). As a result, additional variable moments occur on the output shafts of MM drives, which cannot be determined using only calculations obtained by means of the inverse problem of dynamics solution algorithm.

Identification of external moments on the output shafts of MM electric drives is possible using the Kalman filter [6] and diagnostic observers [7], [8], [9], [10]. But Kalman filters are mainly applicable for linear systems with constant or slowly changing parameters and external influences. Therefore, they cannot be effectively used to identify rapidly changing external moments in underwater MM drives described by complex nonlinear differential equations with significantly and rapidly changing parameters. In contrast to filters, special diagnostic observers can not only detect the appearance of unaccounted moments on the output shafts of MM drives, but also determine their values. But, as analyses have shown, the accuracy of their work is largely determined by the values of the identified functions. In underwater MM, the parameters of their drives and external influences can vary over large ranges (especially when they move quickly), which ultimately leads to significant identification errors and, as a result, to a significant decrease of the movement accuracy of MM gripper along the prescribed trajectories.

2. Problem statement

The report sets and solves the problem of developing a new method for synthesizing combined systems for high-precision movement control of grippers of underwater MM. This method contains three steps. At the first stage, using the recurrent algorithm [3] for solving the inverse problem of dynamics, an analytical calculation of the moments that occur in all degrees of mobility of MM when they move in the water environment is performed. Since this calculation is very approximate due to the complexity of accurately describing and determining the parameters of interaction of all MM links and cargo with the water environment, at the second stage, according to the well-known procedure described in [8], [9], [10] additional diagnostic observers are constructed using dynamic models of electric drives of each degree of mobility of MM, including the external moments approximated at the first stage. These observers, by using the disparity that formed by them, not only detect the occurrence of additional (unrecorded) moments due to the variable interaction of the moving MM with the viscous fluid, but also determine their value fairly accurately, as well as the magnitude of unexpected changes in the moments of viscous and coulomb friction in the electric drive units. All external torque effects determined at the first and second stages on electric drives of all degrees of MM mobility are compensated at the third stage using synthesized self-adjusting correction devices (SACD) [11], ensuring their accurate stabilization at the nominal level.

3. Calculation of the moments that occur in the joints of the MM when it moves in the water environment

To calculate and then compensate for the negative interactions between all the degrees of mobility of MM that occur when it moves at an arbitrary speed in the water environment, we can use a recurrent algorithm for solving the inverse problem of dynamics [3], in which it is assumed that each elementary part of the MM link i with length δh_i^* may have different speeds relative to the stationary fluid, not only by value, but also by direction. In addition, the force acting on this elementary part from the viscous environment can have a linear or quadratic dependence on the value of the movement speed of this part in the water environment. Therefore, each link of the n-dof manipulator in the proposed algorithm is divided into N elementary parts, and the total force acting on the link i is defined as the sum of the forces applied to each elementary part $j = \overline{1, N}$ of this link.

The algorithm for solving the inverse problem of dynamics for underwater MM has the form [3]:

$$\omega_i = A_i^{i-1} \cdot \omega_{i-1} + e_i \cdot \dot{q}_i \cdot \bar{\sigma}_i, \omega_0 = \omega_0^*, i = \overline{1, n};$$
$$\dot{\omega}_i = A_i^{i-1} \cdot \dot{\omega}_{i-1} + \left[\left(A_i^{i-1} \cdot \omega_{i-1}\right) \times e_i \cdot \dot{q}_i + e_i \cdot \ddot{q}_i\right] \cdot \bar{\sigma}_i, \dot{\omega}_0 = \dot{\omega}_0^*, i = \overline{1, n};$$
$$\ddot{P}_i' = A_i^{i-1} \cdot \left(\ddot{P}_{i-1}' + \delta_{i-1} \cdot r_{i-1}^*\right) + (2 \cdot \dot{q}_i \cdot \omega_i \times e_i + \ddot{q}_i \cdot e_i) \cdot \sigma_i, \ddot{P}_0' = P_0'^*, i = \overline{1, n};$$
$$\ddot{r}_{mi} = \ddot{P}_i' + \delta_i \cdot r_i^*, i = \overline{1, n};$$
$$\mathrm{v}_i = A_i^{i-1} \cdot (\mathrm{v}_{i-1} + \omega_{i-1} \times p_{i-1}^*), \mathrm{v}_1 = \mathrm{v}_0, i = \overline{2, n};$$
$$\mathrm{v}_{Ai} = \mathrm{v}_i + \omega_i \times r_i^*, \varphi_i = \arccos \frac{\mathrm{v}_{Ai} \cdot p_i^*}{|\mathrm{v}_{Ai}| \cdot |p_i^*|}, i = \overline{1, n};$$
$$\alpha_i^* = \arccos \frac{\mathrm{v}_i \cdot p_i^*}{|\mathrm{v}_i| \cdot |p_i^*|}, \beta_i^* = \arccos \frac{\omega_i \cdot p_i^*}{|\omega_i| \cdot |p_i^*|}, i = \overline{1, n};$$
$$r_{pi} = r_i^* + K_{Ai} \cdot \mathrm{v}_{Ai}, i = \overline{1, n};$$
$$\mathrm{v}_j^* = \mathrm{v}_i + \omega_i \times h_j^*, \omega_{Li} = |\omega_i| e_{Li} \cos \beta_i^*, i = \overline{1, n}, j = \overline{1, N};$$
$$\mathrm{v}_{Li}^* = |\mathrm{v}_i| e_{Li} \cos \alpha_i^*, \mathrm{v}_{pj}^* = \mathrm{v}_j^* - \mathrm{v}_{Li}^*, i = \overline{2, n}, j = \overline{1, N};$$
$$\mathrm{Re}_{Li} = \frac{\rho \mathrm{v}_{Li}^* l_i}{\eta}, i = \overline{n, 1};$$
$$\text{If } \mathrm{Re}_{Li} \leq 10^3, \text{then } F_{RLi} = k_{Li} \eta \mathrm{v}_{Li}^*, i = \overline{n, 1};$$

if $\mathrm{Re}_{Li} > 10^3$, then $F_{RLi} = \frac{1}{2}\rho k_{Li} s_i {\mathrm{v}_{Li}^*}^2, i = \overline{n,1}$;

$\mathrm{Re}_{pj} = \frac{\rho \mathrm{v}_{pj}^* r_i}{\eta}, i = \overline{n,1}, j = \overline{1,N}$;

if $\mathrm{Re}_{pj} \le 10^3$, then $F_{Rpj} = k_i^* \eta \mathrm{v}_{pj}^*, i = \overline{n,1}, j = \overline{1,N}$;

if $\mathrm{Re}_{pj} > 10^3$, then $F_{Rpj} = \frac{1}{2}\rho k_i^* r_i \delta h_i^* {\mathrm{v}_{pj}^*}^2, i = \overline{n,1}, j = \overline{1,N}$;

$$F_{Rpi} = \sum_{j=1}^{N} F_{Rpj}, i = \overline{n,1}, j = \overline{1,N};\ M_{Rpj} = h_j^* \times F_{Rpj}, j = \overline{1,N};$$

$$M_{Rpi} = \sum_{j=1}^{N} M_{Rpj}, i = \overline{n,1}, j = \overline{1,N};\ M_{Li} = k_{Li}^* \eta r_i \omega_{Li}, i = \overline{n,1};$$

$$F_i = A_i^{i+1} \cdot F_{i+1} + (m_i + \Pi_{mi}) \cdot \ddot{r}_{mi} + F_{RLi} + F_{Rpi}, F_{n+1} = 0, i = \overline{n,1};$$

$$M_i = A_i^{i+1} \cdot M_{i+1} + p_i^* \times \left(A_i^{i+1} \cdot F_{i+1}\right) + r_i^* \times (m_i \cdot \ddot{r}_{mi}) + r_{pi} \times (\Pi_{mi} \cdot \ddot{r}_{mi}) + (\tau_i + T_i) \cdot \dot{\omega}_i +$$
$$+\omega_i \times \left((\tau_i + T_i) \cdot \omega_i\right) + M_{Rpi} + M_{Li}, M_{n+1} = 0, i = \overline{n,1};$$

where $\delta_i = \begin{bmatrix} -\left(\omega_{i(2)}^2 + \omega_{i(3)}^2\right) & \omega_{i(1)} \cdot \omega_{i(2)} - \dot{\omega}_{i(3)} & \omega_{i(1)} \cdot \omega_{i(3)} + \dot{\omega}_{i(2)} \\ \omega_{i(1)} \cdot \omega_{i(2)} + \dot{\omega}_{i(3)} & -\left(\omega_{i(1)}^2 + \omega_{i(3)}^2\right) & \omega_{i(2)} \cdot \omega_{i(3)} - \dot{\omega}_{i(1)} \\ \omega_{i(1)} \cdot \omega_{i(3)} - \dot{\omega}_{i(2)} & \omega_{i(2)} \cdot \omega_{i(3)} + \dot{\omega}_{i(1)} & -\left(\omega_{i(1)}^2 + \omega_{i(2)}^2\right) \end{bmatrix}$ (a subscript in round brackets indicates the number in the respective vectors); $\mathrm{v}_i \in R^3$ is the linear velocity of the joint i; $\omega_i \in R^3$ is the angular velocity of rotation of the link i; $p_i^* \in R^3$ is the vector coincident with the longitudinal axis of the link i, defining the position of the hinge $(i+1)$ relative to the hinge i; $\mathrm{e}_{Li} \in R^3$ is the unit vector directed along the longitudinal axis of the link i; $h_i^* \in R^3$ is the vector defining the center of mass of the elementary part j of the link i with the length δh_j^* relative to the hinge i; l_i and r_i are respectively the length and radius of the link i; A_i^{i-1} is the matrix of translation of vectors from $(i-1)$ to the i coordinate system; $e_i = (0\ 0\ 1)^T$ is the unit vector directed along the axis of the joint i; $\mathrm{v}_0 \in R^3$ is the linear velocity of the MM attachment point to the underwater vehicle, $\omega_i^* \in R^3$ is the angular velocity of the vehicle rotation; q_i is the generalized coordinate i of the MM; $\mathrm{v}_j^* \in R^3$ is the linear speed vector of moving of center of mass of each element j of the link i; $\mathrm{v}_{Li}^* \in R^3$ and $\mathrm{v}_{pj}^* \in R^3$ are respectively the longitudinal and transverse components of the vector v_j^*; Re_{Li} and Re_{pj} are respectively the Reynolds numbers when moving the MM links parallel and perpendicular to their longitudinal axes; ρ и η are respectively the density and viscosity of a liquid; k_{Li}^*, k_i^* and k_{Li} are the experimentally determined coefficients of a viscous friction; s_i is the ground area of the cylindrical link i; $F_{Rpj} \in R^3$ is the component of the viscous friction force acting on the corresponding elementary part j of the link i, directed perpendicular to the longitudinal axis of the link; $F_{RLi} \in R^3$ is the component of the viscous friction forces, directed along the longitudinal axis of the MM link i; $M_{Rpj} \in R^3$ is the moment created by the force F_{Rpj}; $F_{Rpi} \in R^3$ is the total force created by the forces F_{Rpj}; $M_{Rpi} \in R^3$ is the moment created by the force F_{Rpi}; $\mathrm{v}_{mi} \in R^3$ is the linear velocity of the center of mass of the link i; $\sigma_i = 1$ if joint i is translational and $\sigma_i = 0$, if it is rotational ($\bar{\sigma}_i = 1 - \sigma_i$); m_i is the mass of the link i; $\dot{\omega}_i \in R^3$ is the angular acceleration of the link i; $\omega_{Li} \in R^3$ is the component of the angular velocity ω_i, parallel to the longitudinal axis of the link i; $M_{Li} \in R^3$ is the moment produced by the rotation of the link i with the speed ω_{Li}; Π_{mi} is the mass of a fluid attached to the link i; $\ddot{r}_{mi} \in R^3$ is the linear acceleration of the link i center of mass; $r_{pi} \in R^3$ is the vector defining position of the center of mass Π_{mi} relative to the joint i; r_i^* is the vector that specifies the center of mass of the link i relative to the joint i; K_{Ai} is the parameter that depends on $|\mathrm{v}_{Ai}|$ and the angle φ_i; $\tau_i \in R^{3\times3}$ is the link i inertia tensor about its center of mass; $T_i \in R^{3\times3}$ is the inertia tensor of the mass of a fluid attached to the link i; $F_i, M_i \in R^3$ are force and moment acting at the joint i; $P_0'^* = -g + P'_{UV}$, if the centers of mass of all MM links do not coincide with their centers of buoyancy; $P_0'^* = g\left(\frac{w_i}{m_i} - 1\right) + P'_{UV}$, if the centers of mass of all links of the MM coincide with their centers of value; $\ddot{P}'_{UV} \in R^3$ is the linear acceleration of the MM base; g is the gravitational acceleration of a body; w_i is the mass of a liquid displaced by the link i; $(\times)$ and $(\cdot)$ are vector and scalar products of vectors, respectively.

As a result, the calculated external moment $P_i(t)$, acting on the output shaft of the i-th MM electric drive, will be determined by the equality $P_i(t) = M_{i(3)}(t)$, where the subscript 3 in round brackets indicates the element number in the corresponding vector $Mi(t)$. In what follows, for simplicity of the introduced designations, the indices i, denoting the number of the corresponding MM degree of mobility, will be omitted.

4. Description of diagnostic observers

As noted above, accurate a priori determination of the MM parameters, its electric drives and a viscous fluid, and even more so of the objects being moved, is almost always difficult. In addition, unexpected changes may occur during the work execution. As a result, it is not possible to provide high-quality MM control using only the algorithm for solving the inverse problem of dynamics. For more accurate determination of the features of external influences on MM electric drives, additional diagnostic observers should be synthesized and used at the second stage, as discussed below.

Equations of electric drives of the underwater MM with the introduction of phase coordinates $x_1(t) = q(t), x_2(t) = \dot{\alpha}(t), x_3(t) = I(t)$, measured by the corresponding sensors, and the P value calculated above can be represented in matrix form

$$\dot{x}(t) = Ax(t) + Bu(t) + G\big(x_2(t), P^*(t)\big) + Dd(t), \quad (1)$$

where $A = \begin{bmatrix} 0 & 1/i_p & 0 \\ 0 & -k_v/J_\Sigma & k_M/J_\Sigma \\ 0 & -k_\omega/L & -R/L \end{bmatrix}$; $x(t) = \begin{bmatrix} q(t) \\ \dot{\alpha}(t) \\ I(t) \end{bmatrix}$; $B = \begin{bmatrix} 0 \\ 0 \\ k_g/L \end{bmatrix}$; $G(t) = \begin{bmatrix} 0 \\ \frac{-M_{clmb}(x_2(t)) - P^*(t)}{J_\Sigma} \\ 0 \end{bmatrix}$; $D = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$; $q(t)$ is the angle of rotation of the output shaft of the electric drive unit; $\dot{\alpha}(t)$ is the rotation speed of the motor rotor; R, L, $I(t)$ are the active resistance, inductance and current of the armature circuit, respectively; k_ω, k_M, k_g are the coefficients of counter-EMF, moment and amplifier gain; $u(t)$ is the input voltage; J_Σ is the moment of inertia of the motor rotor and rotating parts of the gearbox, given to this rotor; k_v is the nominal coefficient of viscous friction; M_{clmb} is the nominal coulomb friction moment of the motor and its gearbox; $M_{clmb} = \begin{cases} M_{fr} sign(x_2(t)), & \text{if } x_2(t) \neq 0 \\ 0, & \text{if } x_2(t) = 0 \end{cases}$, M_{fr} is the value of the coulomb friction moment of movement; $P^*(t) = P(t)/i_p$ – moment $P(t)$, brought to the motor rotor; i_p – differential ratio of gearbox.

In equation (1) the function $d(t)$ defines an unknown total moment effect described by the equation

$$d(t) = -\frac{1}{J_\Sigma}\left[\tilde{k}_v x_2(t) + \tilde{M}_{clmb}\big(x_2(t)\big) + \tilde{P}^*(t)\right],$$

where $\tilde{k}_v$, $\tilde{M}_{clmb}(x_2(t))$, $\tilde{P}^*(t)$ are the values of deviations of the viscous friction coefficient and the coulomb friction moment from their nominal values, as well as $\tilde{P}^*(t)$ is the value of deviation of external moments from the calculated value of $P^*(t)$, respectively.

To identify the value $d(t)$, we can use diagnostic observers synthesized using methods described in [8], [9], [10]. Desired observer equation can be described by the formula

$$\dot{x}_*(t) = A_* x_*(t) + B_* u(t) + G_* + J_* y(t) - k e_y(t) + D_* v(t), \ (J_* \in R^3), \quad (2)$$

where the symbol «*» is marked on the bottom of the matrix and vectors describing the observer, the elements of which differ from the corresponding elements of the matrices and vectors of the models of drives (2); k is a positive constant; $e_y(t) = \Phi x(t) - x_*(t) \in R^3$ is the disparity that allows to set differences between parameters of respective actuators of the MM from their nominal values in the system (2) (if $e_y(t) \neq 0$ and $d(t) \neq 0$); $\Phi \in R^3$ is the vector to be determined; the function $v(t)$ has the form $v(t) = \begin{cases} -g^* \frac{e_y(t)}{|e_y(t)|}, & \text{if } e_y(t) \neq 0, \\ 0 & \text{else}, \end{cases}$, g^* is the positive constant.

When synthesizing the observer that determines the appearance of a non-zero function $d(t)$ in the system (1), one should define the matrices A_*, B_* and vectors J_*, Φ. By introducing the well-known condition [9], [10] $\Phi D \neq 0$ of the dependence of the disparity on $d(t)$, the vector Φ can be formed as $\Phi = [0 \ 1 \ 0]$.

It is advisable to solve the problem of constructing diagnostic observers in the canonical Kronecker form [9], [10]. In this case, taking into account the dimension of the synthesized observers, the equality $A_* = 0$ is valid. Given this equality and the validity of the relations $J_* = \Phi A$, $B_* = \Phi B$, $G_* = \Phi G$, $D_* = \Phi D$ [9], [10], the desired observer can be described by the equation

$$\dot{x}_*(t) = -\frac{k_v}{J_\Sigma}\dot{\alpha}(t) + \frac{k_M}{J_\Sigma}I(t) - \frac{M_{clmb}\big(x_2(t)\big)}{J_\Sigma} - \frac{P^*(t)}{J_\Sigma} - k e_y(t) + v(t). \quad (3)$$

It is known [11] that when $g_* > |d(t)|$ is chosen, the observer (3) converges asymptotically, i.e. the estimation error $e_y(t) = \Phi x(t) - x_*(t) \to 0$ when $t \to \infty$. In this case, the value d(t) can be estimated with high accuracy using a low-pass filter [12]: $\hat{d}(t) = v_f(t)$, where $\hat{d}(t)$ is the estimate of the function $d(t)$ obtained by the observer (3); $v_f(t)$ is the value of the function $v(t)$ passed through the low–pass filter.

Thus, the use of additional observers (4) for electric drives of each MM degree of mobility provides detection and evaluation of the values of unaccounted moments that appear due to inaccuracy in calculating the value of $P^*(t)$, as well as deviations of the moments of viscous and coulomb friction in these drives from their nominal values.

5. Synthesis of self-adjusting correction devices for MM electric drives

The third stage of solving the task is the synthesis of the SACD for all electric drives of the MM for stabilization of their dynamic properties and, hence, accuracy of work with the rapid changes of the external moments, and the changing moments of coulomb and viscous friction in these drives. It is proposed to synthesize these SACD using an approach based on the stabilization of the parameters of differential equations describing MM electric drives [11]. To do this, it is necessary to rewrite the differential equation of each loaded electric drive (1), taking into account that when they move, the equality $\dot{M}_{\text{clmb}} = 0$ is valid:

$$u(t)k_g k_{\text{м}} = LJ_\Sigma \dddot{\alpha}(t) + (k_{\text{v}}L + J_\Sigma R)\ddot{\alpha}(t) + (Rk_{\text{v}} + k_\omega k_{\text{м}})\dot{\alpha}(t) + L\left(\dot{P}^*(t) + \dot{\hat{d}}(t)\right) + \\ +R\left(P^*(t) + \hat{d}(t) + M_{\text{clmb}}\right). \quad (4)$$

The desired linear differential equation for each electric drive with nominal constant parameters and stable dynamic properties has the form:

$$\hat{u}(t)k_g k_{\text{м}} = LJ_\Sigma \dddot{\alpha}(t) + J_\Sigma R\ddot{\alpha}(t) + k_\omega k_{\text{м}}\dot{\alpha}(t), \quad (5)$$

where $\hat{u}(t)$ is the control signal received at the input of the SACD.

Expressing the value of the highest derivative $\dddot{\alpha}(t)$ from the equation (5) and substituting it into the original equation (4), it is easy to obtain the desired control law. Given that in modern electric drives of the MM the electrical time constant is usually small $\left(\frac{L}{R} \ll 1\right)$, so this equation will have the form:

$$u(t) = \frac{1}{k_g k_{\text{м}}}\left[k_{\text{v}}R\dot{\alpha}(t) + R\left(P^*(t) + \hat{d}(t)\right) + M_{\text{clmb}}R\right] + \hat{u}(t). \quad (6)$$

6. Simulation results

To explore the features of the synthesized control system functioning in the Matlab Simulink, the simulation of the operation of a three-dof MM with a PUMA kinematic scheme [13], which has only three translational degrees of mobility, was performed. Its gripper was moving along the sinusoidal trajectory $f_y(x^*) = 0.5\sin(10x) + 0.05$, $f_z(x^*) = 0.01$, which was set using the trajectory generator [14], with a constant speed of 0.6 m/s.

When modeling the work, the MM parameters described in [13] were used. It was assumed that in all degrees of mobility of MM the same electric drives with DC motors of independent excitation or permanent magnets were installed, having the following parameters: $J_\Sigma = 0.0001$ kgm², $R = 0.2$ Ohm, $k_{\text{y}} = 35$, $i_p = 100$, $k_\omega = 0.02$ Vs, $k_{\text{м}} = 0.02$ Nm/A, $k_{\text{в}} = 0.005$ Nms/rad, $M_{\text{fr}} = 0.06$ Nm, $L = 0.002\,H$. Observers (3) with parameters $k = 10$ и $g_* = 7000$ were used for each electric drive. All electric drives used the SACD (6), and standard additional correction devices – PID-regulators with the following coefficients: $k_P = 10, k_I = 0.01, k_D = 0.4$.

To simulate additional external moments $\tilde{P}^*(t)$ that occur in MM electric drives, the algorithm for solving the inverse problem of dynamics used 20% increased values of viscous friction coefficients, attached masses, and moments of inertia of a liquid. The moments $(P^*(t) - \tilde{P}^*(t))$ calculated this way fed to MM electric drives. In addition, at time $t = 2$ sec in electric drives of all MM degrees of mobility, the coefficients of viscous friction and coulomb friction moments increased by 20 % of their nominal values.

Figure 1 shows the values of dynamic errors $\varepsilon(t)$ of the gripper movement along the given program trajectory: without using synthesized SACD in MM electric drives (curve 1), with using of SACD (6) (curve 2) taking into account only the calculated values of $P^*(t)$, and the curve 3 shows the accuracy of the system with using of additional observers (3).

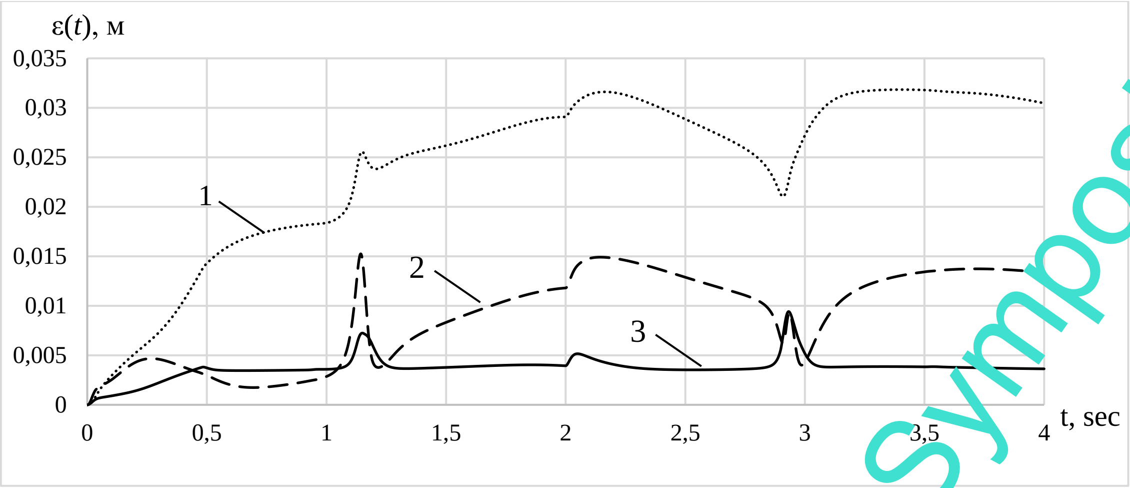

Figure 1 – Values of dynamic errors at the MM gripper movements along the given trajectory

From the presented graphs, it can be seen that the error value without using the SACD reaches 32 mm, and with using of the SACD, this error does not exceed 15 mm. At the same time, the use of additional observers that allow taking into account the values of moments leads to a decrease of the dynamic error of movement of the MM gripper to 0.4 mm in most of trajectory areas.

Thus, the results of numerical simulation confirmed the operability of the synthesized system, which allows to significantly increase the accuracy of various technological operations performed by the underwater MM at high speed.

7. Conclusion

The report describes solving of the problem of increasing the accuracy of the underwater MM gripper movement when it moves in a liquid at high speed. To solve the presented problem, the new three-stage method for synthesizing a combined system for high-precision movement control of an underwater MM was developed. At the first stage of the proposed method, using a recurrent algorithm for solving the inverse problem of dynamics, an approximate calculation of the moments that occur in all MM degrees of mobility when it moves in a water environment was performed. At the second stage, using dynamic models of electric drives of each MM degree of mobility, including approximately calculated external moments, additional observers were built. The use of these observers provides detection and estimation of the values of unaccounted moments that occur in the MM degrees of mobility when it moves in a viscous fluid, as well as deviations of the moments of viscous and coulomb friction in the drives from their nominal values. All external moment effects determined at the first and second stages on the output shafts of the electric drive rotors of all degrees of mobility are compensated by means of SACD at the third stage. Simulation results confirmed the efficiency of the synthesized system. Usage of this system makes it possible to reduce the MM gripper dynamic positioning error multiple times. It should be noted that the greatest efficiency of the method is achieved when the underwater vehicle is rigidly fixed near the object of work. If the vehicle is in hang mode, it is necessary to take into account the capabilities of the stabilization system to compensate the negative dynamic effects from the moving MM. Therefore, further research will focus on the development of methods for generating such a speed of the MM at which the stabilization system will allow the underwater vehicle to be held near the object of work.

8. Acknowledgements

This work was performed in Institute of Marine Technology Problems FEB RAS, Institute for Automation and Control Processes FEB RAS and also in Far Eastern Federal University (Vladivostok, Russia).

This work was supported by the Russian Foundation for Basic Research, project no. 20-38-70161, no. 19-08-00347_A, no. 18-08-01204.

9. References

[1] Filaretov V.F., Konoplin N.Yu., Konoplin A.Yu. (2019). System for automatic soil sampling by AUV equipped with multilink manipulator // International Journal of Energy Technology and Policy, Vol.15 No.2/3, pp.208 – 223, DOI: 10.1504/IJETP.2019.098965.

[2] Konoplin A.Yu., Konoplin N.Yu., Shuvalov B.V. (2019). Technology for Implementation of Manipulation Operations with Different Underwater Objects by AUV // International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM). DOI: 10.1109/ICIEAM.2019.8743094.
[3] Filaretov V.F., Konoplin A.Yu. (2015). System of Automatic Stabilization of Underwater Vehicle in Hang Mode with Working Multilink Manipulator. // International Conference on Computer, Control, Informatics and Its Applications (IC3INA). Bandung, Indonesia. International IEEE Conference. 2015. pp. 132-137. DOI: 10.1109/IC3INA.2015.7377760.
[4] P. Coiffet. (1983). Robot Technology: Interaction with the environment. Kogan Page Ltd. London. 290p.
[5] Filaretov V.F., Konoplin A.Yu. (2015). Experimental Definition of the Viscous Friction Coefficients for Moving Links of Multilink Underwater Manipulator // Proceedings of the 26th DAAAM International Symposium, Vienna, Austria, pp.0762-0767, ISBN 978-3-902734-07-5, DOI:10.2507/26th.daaam.proceedings.106.
[6] Zhang Q. (2018). Adaptive Kalman filter for actuator fault diagnosis // Automatica. Vol. 93. P. 333-342.
[7] He J., Zhang C. (2012). Fault reconstruction based on sliding mode observer for nonlinear systems // Mathematical Problems in Engineering. V. 2012. ID 451843. P. 1-22.
[8] Zhirabok A.N., Shumsky A.E., Zuev A.V. (2019). Fault diagnosis in linear systems via sliding mode observers // International Journal of Control. P.1-9.
[9] Zhirabok, A., Shumsky, A., and Pavlov, S. (2017). Diagnosis of Linear Dynamic Systems by the Nonparametric Method // Autom. Remote Control, vol. 78, no. 7, pp. 1173-1188.
[10] Filaretov V., Zhirabok A., Zuev A., Protcenko A. (2016) Fault identification in nonlinear dynamic systems // Proc. of the 5th International Conference on Systems and Control, ICSC. P. 273-277
[10] Filaretov V.F. (2007). Synthesis of Adaptive Control Systems for Electric Servo Actuators of Manipulators. Proc. of the 18th DAAAM Int. Symp. «Intelligent Manufacturing & Automation». Zadar, Croatia, pp. 277-278.
[11] Utkin V.I. (1992). Sliding Modes in Control and Optimization. Springer-Verlag. 286 p.
[12] Filaretov V.F., Konoplin A.Yu. (2015). System of Automatically Correction of Program Trajectory of Motion of Multilink Manipulator Installed on Underwater Vehicle // Procedia Engineering, Vol 100. pp. 1441-1449, ISSN 1877-7058, DOI: 10.1016/j.proeng.2015.01.514.
[13] Filaretov V.F., Yukhimets D.A., Konoplin A.Yu. (2014). Synthesis of System for Automatic Formation of Multilink Manipulator Velocity// The Second RSI International Conference on Robotics and Mechatronics (ICRoM 2014). Tehran IRAN. International IEEE Conference. pp. 785-790. DOI: 10.1109/ICRoM.2014.6990999.