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System of Automatically Correction of Program Trajectory of Motion of Multilink Manipulator Installed on Underwater Vehicle

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Abstract

In this work method of synthesis of system of automatic correction of program trajectory of motion of multilink manipulator installed on underwater vehicle was discussed. Developed system allows solving problem of fast and high quality performing of underwater manipulation operations with less operator fatigue at underwater vehicle hang mode near object of work even at unintended displacements of underwater vehicle from initial position. Using of synthesized system is assumed with well-known systems of automatic stabilization of underwater vehicle in desirable point of space.
Proposed automatic correction provides additional movements of multilink manipulator effector. This correction is based on information about actual angular and linear displacements of underwater vehicle from initial position and information about constantly varied configuration of multilink manipulator.
Results of performed mathematical modeling have confirmed high efficiency of synthesized system.

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Keywords: underwater vehicle; control system; multilink manipulator; automatic correction; trajectory of movement

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1. Introduction

Today underwater vehicles (UV) [1, 2] which have multilink manipulators (MM) [3-5] actively used for research and development of World Ocean. Many complex technological operations are possible to perform at any depth using UV with MM. Tasks of fast and qualitative performance of underwater manipulation operations have greatest relevance in UV hang mode near object of work. Some systems of UV automatic stabilization in hang mode with working manipulator [3, 4] are created today. These systems allow solving problem of fast and high quality performing of manipulation operations with less operator fatigue. Herewith generally, desired trajectory of MM effector motion gets and sets before operating. MM effector should precisely move on specified trajectory after entrance of UV in given point in space with given orientation (possibly in manual mode).

However, working in hang mode UV unplanned displaces from desirable position under influences of sea currents and swell, as well as forces and torques effects from umbilical and working manipulator, even at presence of auto-stabilization systems which have limited accuracy. Displace of UV makes it difficult to automatically performing many manipulative operations. As a result, there arises necessity of using of additional automatic correction of program trajectory of motion of MM effector in process of its movement. Automatic correction should base on information about actual angular and linear displacements of UV from initial position and information about constantly varied MM configuration. Said correction should provide additional moving of MM effector. Herewith information about actual angular and linear displacement of UV obtained from high-precision navigation and gyroscopic systems.

2. Description of underwater manipulation system and problem statement

UV with fixed (in point *O*) *n* – degrees MM showed on Fig. 1. MM is able to move in forward hemisphere in front of UV. Each MM degree of freedom is actuated by corresponding actuator. In this figure: *1* - given (constant) desired spatial trajectory of MM effector movement; *2* – UV in origin position; *3* – underwater MM in origin position; *4* - UV in new position displaced from original position; *5* - new configuration of underwater MM which ensures accurate passing of MM effector along trajectory *1*. Origins of absolute *XYZ* and body-fixed $X^*Y^*Z^*$ with UV right rectangular coordinate systems (SC) are combined in origin position *2* with UV centre of weights *C*, which coincides with centre of its size. Herewith axes of SC *XYZ* and $X^*Y^*Z^*$ are coincide in UV origin position *2*. Axes of body-fixed SC $X^*Y^*Z^*$ are coinciding with UV axes of symmetry and axis Y^* is longitudinal axis of UV. Vector $P^*(t) \in R^3$ sets current desired position of characteristic point *A* of MM effector in SC $X^*Y^*Z^*$, in which MM works. Vector $P(t)^T \in R^3$ sets position of point *A* in SC XYZ. Vector $P_C(t) \in R^3$ sets offset of point *C* in SC XYZ. Coordinates of point *A* in SC XYZ are determined by formulas [6]:

$$\begin{cases} \dot{y} = v(t)/\Phi(y), \\ x = g_x(y), \\ z = g_z(y), \end{cases} \tag{1}$$

where $v(t)$ - module of vector of desired speed of point *A* movement along trajectory *1*; $g_x(y), g_z(y)$ - functions describing corresponding projections of trajectory of point *A* motion on axis of SC *XYZ*; $\Phi(y) = \sqrt{(\frac{dg_x(y)}{dy})^2 + (\frac{dg_z(y)}{dy})^2 + 1}.$

In this figure shown that when UV deviates from origin position during manipulation operation $x^* \neq x$, $y^* \neq y$, $z^* \neq z$. Therefore, expression (1) cannot be used for determine trajectory of MM effector movement in SC $X^*Y^*Z^*$.

Shall assume that UV is equipped with high-accuracy navigation system, which allows to determine position of UV with accuracy of at least 0.01м [7-10]. Also UV is equipped with onboard gyroscopes which precisely measure angles of roll, pitch and yaw of UV, special system of automatic stabilization of UV in space [3,4] which provides acceptable compensation of forces and torques effects to UV from working MM by UV propulsion thrusts.

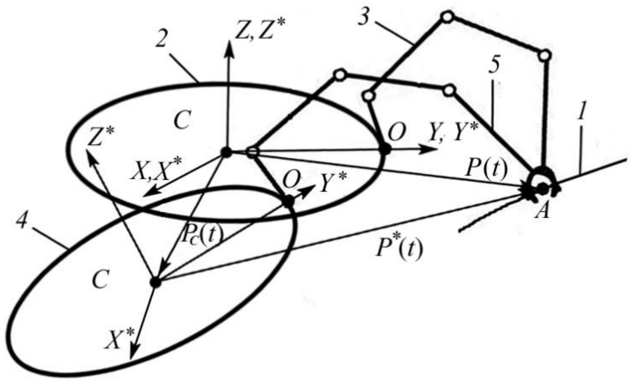

Fig. 1. UV and layout of SC.

It is necessary to synthesize system, which allows to operate MM effector so that it always moving along trajectory continuously calculated in SC XYZ by formula (1). Wherein said system should automatically determine position of point A in SC $X^*Y^*Z^*$ based on measurement of current UV displacements (with SC $X^*Y^*Z^*$) relative to its initial position. In this case, angular and linear UV displacements (in presence of above-mentioned system of UV automatic stabilization) should not exceed certain limits depending on parameters and kinematic scheme of MM. Namely, MM should be able to recoup arising UV displacements during tracking of point on trajectory.

3. Construction of system of automatic correction of program motion trajectory of MM effector

Shall assume that point C was displaced relatively to origin of SC XYZ and SC $X^*Y^*Z^*$ was arbitrarily turned in SC XYZ when MM is working. Onboard gyroscopes measure trim angle α formed by longitudinal axis Y^* of UV and horizontal plane (see Fig. 2). Yaw angle β is formed by projection $Y^{*'}$ of longitudinal axis Y^* on horizontal plane and direction of axis Y. Roll angle γ is formed by turning of UV around its longitudinal axis Y^* [11]. Wherein coordinate $\Delta x(t)$, $\Delta y(t)$ and $\Delta z(t)$ of vector $P_C(t) \in R^3$ which determined offset of point C in SC XYZ (see Fig. 1) relatively to original position of UV are measured by precision navigation system.

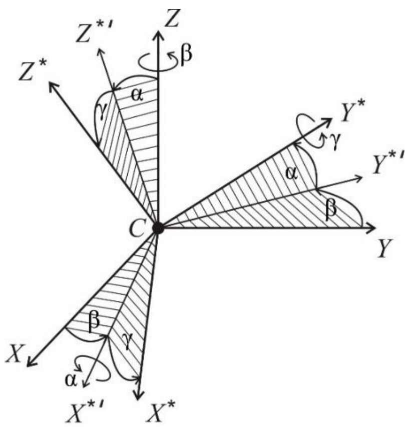

Fig. 2. Angle displacements of body-fixed SC.

To solve this problem it is necessary to find elements of vector $P^*(t)$ in SC $X^*Y^*Z^*$, knowing elements of vectors $P(t)$ and $P_C(t)$ in SC XYZ . Obviously, elements of vector $P^*(t)$ in SC XYZ can be obtained by subtracting of two vectors $P(t)-P_C(t)$ (see Fig. 1), and elements of this vector in SC $X^*Y^*Z^*$ can be obtained using equation:

$$P^*(t)=R^T\left(P(t)-P_C(t)\right), \tag{2}$$

where $R\in R^{3\text{x}3}$ - matrix of rotation of SC $X^*Y^*Z^*$ relative to XYZ [12], T – symbol of transposition.

For definition of elements of matrix R UV rotation with SC $X^*Y^*Z^*$ must be presented as sequence of elementary rotations. Axes relative to which angles of corresponding rotations of SC $X^*Y^*Z^*$ and sequence of these rotations are measuring must be selected such that angles α and γ will be really measured by onboard gyroscope. This condition is carried out at following sequence of elementary rotations of CS $X^*Y^*Z^*$ (see Fig. 2): firstly SC $X^*Y^*Z^*$ rotates around axis Z at angle β (matrix of elementary rotation $R_{Z,\beta}$ corresponds to it). After SC rotates around displaced axis $X^{*}{}'$ at angle α (matrix of elementary rotation $R_{X^*{}',\alpha}$ corresponds to it). After SC rotates around axis Y^* at angle γ (matrix of elementary rotation $R_{Y^*,\gamma}$ corresponds to it). These rotation matrices have standard form [13]:

$$R_{X^*{}',\alpha}=\begin{bmatrix}1 & 0 & 0\\ 0 & C\alpha & -S\alpha\\ 0 & S\alpha & C\alpha\end{bmatrix}, R_{Y^*,\gamma}=\begin{bmatrix}C\gamma & 0 & S\gamma\\ 0 & 1 & 0\\ -S\gamma & 0 & C\gamma\end{bmatrix}, R_{Z,\beta}=\begin{bmatrix}C\beta & -S\beta & 0\\ S\beta & C\beta & 0\\ 0 & 0 & 1\end{bmatrix}, \tag{3}$$

where $S\alpha=\sin\alpha$; $S\beta=\sin\beta$; $C\alpha=\cos\alpha$; $C\beta=\cos\beta$; $C\gamma=\cos\gamma$. With regard to formulas (3), matrix R for described sequence of rotations of SC $X^*Y^*Z^*$ with UV is given by formula:

$$R=R_{Z,\beta}\;R_{X^*{}',\alpha}\;R_{Y^*,\gamma}=\begin{bmatrix}C\beta C\gamma-S\alpha S\beta S\gamma & -S\beta C\alpha & S\gamma C\beta+S\alpha S\beta C\gamma\\ S\beta C\gamma+S\alpha S\gamma C\beta & C\alpha C\beta & S\beta S\gamma-S\alpha C\beta C\gamma\\ -S\gamma C\alpha & S\alpha & C\alpha C\gamma\end{bmatrix}. \tag{4}$$

It needs to be emphasized, that for determining elements of vector $P^*(t)$ in expression (2) only matrix (4) can be used. Because any matrix compiled by different sequence of elementary rotations can not be implemented using information from onboard gyroscopes.

After substituting of transposed matrix R in equation (2) we have:

$$P^*(t)=\begin{bmatrix}(C\beta C\gamma-S\alpha S\beta S\gamma)(x-\Delta x)+(S\beta C\gamma+S\alpha S\gamma C\beta)(y-\Delta y)-S\gamma C\alpha(z-\Delta z)\\ -S\beta C\alpha(x-\Delta x)+C\alpha C\beta(y-\Delta y)+S\alpha(z-\Delta z)\\ (S\gamma C\beta+S\alpha S\beta C\gamma)(x-\Delta x)+(S\beta S\gamma-S\alpha C\beta C\gamma)(y-\Delta y)+C\alpha C\gamma(z-\Delta z)\end{bmatrix}.$$

Generalized scheme of developed system of automatic correction of program motion trajectory of MM effector is shown on Fig. 3. Following notations introduced in Fig. 3: CS – control system of MM actuators; FPS – unit of forming of MM program signals; CMT - unit of correction of MM motion trajectory; NS – navigation system of UV; H - gyro unit; $P_o(t)=[x_0,y_0,z_0]^T\in R^3$ - vector of initial position of MM effector in SC XYZ ; IPK - unit of solving of inverse kinematics problem of MM; DPK - unit of solving of direct kinematics problem of MM; $Q^*(t)=[q_1^*(t),q_2^*(t),...,q_n^*(t)]^T\in R^n$ - vector of desired values of generalized coordinates of MM;

$Q(t)=[q_1(t),q_2(t),...,q_n(t)]^T\in R^n$ - vector of real values of generalized coordinates of MM; $P_k(t)=[x_k,y_k,z_k]^T\in R^3$ - vector of real position of MM effector in SC XYZ;

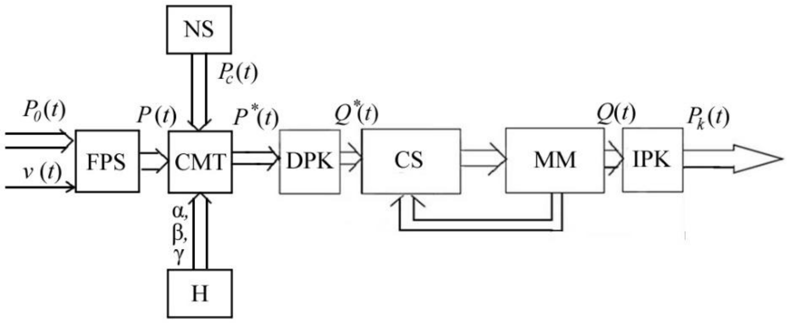

Fig. 3. Generalized scheme of developed system of automatic correction of program motion trajectory of MM effector which mounted on UV.

4. Investigation of synthesized system

We used PUMA MM for investigation of synthesized system. Kinematic scheme of said MM has three degrees of freedom and shown on Fig. 4. Following notations introduced in fig. 4: l_1 = 0.05 m, $l_2=l_3$ = 0.5 m – lengths of MM links; m_1 = 0.4 kg, $m_2=m_3$ = 3.9 kg – masses of these links. Assume that inaccurate stabilized in space base of MM changes its linear and angular coordinates by laws: $P_C(t)=[0.05\sin(2t), -0.04\sin(1.5t), 0.03\sin(2t)]^T$; $\alpha=0.06\sin(2.5t)$; $\beta=0.04\cos(2t)$; $\gamma=0.06\cos(2t)$.

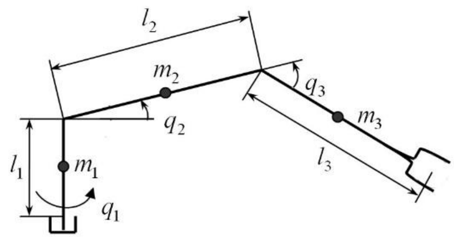

Fig. 4. Kinematic scheme of MM.

MM links centers of size coincide with their centers of masses each of links has a cylindrical shape with base radius $\hat{r}$ = 0.05 m and neutral buoyancy. Inertia tensors relatively to MM links centers of mass are diagonal, and $\tau_{1_{11}}$ = 5* 10^{-4} , $\tau_{1_{22}}=\tau_{1_{33}}$ = 3.3* 10^{-4} - elements of inertia tensor τ_1 of first link; $\tau_{2_{11}}=\tau_{3_{11}}$ = 5* 10^{-3} , $\tau_{2_{22}}=\tau_{2_{33}}=\tau_{3_{22}}=\tau_{3_{33}}$ = 8.4*10^{-2} - elements of inertia tensors τ_2 and τ_3 of second and third links.

For definition of forces and moments that arises in MM joints, we use algorithm for solving inverse dynamics problem of MM by formulas [3]:

$$\omega_i=A_i^{i-1}\cdot\omega_{i-1}+e_i\cdot\dot{q}_i,\ \omega_0=\omega^*{}_0,\ i=\overline{1,n};$$
$$\dot{\omega}_i=A_i^{i-1}\cdot\dot{\omega}_{i-1}+\left[(A_i^{i-1}\cdot\omega_{i-1})\times e_i\cdot\dot{q}_i+e_i\cdot\ddot{q}_i\right],\ \dot{\omega}_0=\dot{\omega}^*{}_0,\ i=\overline{1,n};$$
$$\ddot{P}_i'=A_i^{i-1}\cdot(\ddot{P}_{i-1}'+\delta_{i-1}\cdot p_{i-1}^*),\ddot{P}_0'=\ddot{P}_{UV},i=\overline{1,n};$$
$$\ddot{r}_{mi}=\ddot{P}_i'+\delta_i\cdot r_i^*,\ i=\overline{1,n};$$

$$\mathrm{v}_i = A_i^{i-1}\cdot(\mathrm{v}_{i-1}+\omega_{i-1}\times p_{i-1}^*),\ \mathrm{v}_1=\mathrm{v}_0,\ i=\overline{2,n};$$
$$\mathrm{v}_{Ai}=\mathrm{v}_i+\omega_i\times r_i^*,\ i=\overline{1,n};$$
$$\psi_i=\arccos\frac{\mathrm{v}_{Ai}\cdot p_i^*}{|\mathrm{v}_{Ai}|\cdot|p_i^*|},\ \alpha_i=\arccos\frac{\mathrm{v}_i\cdot p_i^*}{|\mathrm{v}_i|\cdot|p_i^*|},\ \beta_i=\arccos\frac{\omega_i\cdot p_i^*}{|\omega_i|\cdot|p_i^*|},i=\overline{1,n};$$
$$r_{pi}=r_i^*+K_{Ai}\cdot\mathrm{v}_{Ai},\ i=\overline{1,n};$$
$$\mathrm{v}_{pi}=\mathrm{v}_i\cdot\sin\alpha_i,\ \mathrm{v}_{Li}=\mathrm{v}_i\cdot\cos\alpha_i,i=\overline{2,n};$$
$$\omega_{pi}=\omega_i\cdot\sin\beta_i,\ \omega_{Li}=\omega_i\cdot\cos\beta_i,i=\overline{1,n};$$
$$F_{Li}=\eta\cdot k_{Li}\cdot\mathrm{v}_{Li},\ F_{pi}^{\mathrm{v}}=\eta\cdot k_{pi}\cdot\mathrm{v}_{pi},\ F_{pi}^{\omega}=\frac{1}{2}k_{pi}^*\cdot\eta\cdot(\omega_{pi}\times p_i^*),i=\overline{n,1};$$
$$M_{pi}^{\mathrm{v}}=\frac{1}{2}p_i^*\times F_{pi}^{\mathrm{v}},\ M_{pi}^{\omega}=\frac{2}{3}p_i^*\times F_{pi}^{\omega},\ M_{Li}=\eta\cdot k_{Li}^*\cdot\hat{r}_i^2\cdot|\omega_{Li}|\cdot\frac{p_i^*}{|p_i^*|},i=\overline{n,1};$$
$$F_i=A_i^{i+1}\cdot F_{i+1}+(m_i+\Pi_{mi})\cdot\ddot{r}_{mi}+F_{Li}+F_{pi}^{\mathrm{v}}+F_{pi}^{\omega},\ F_{n+1}=0,\ i=\overline{n,1};$$
$$M_i=A_i^{i+1}\cdot M_{i+1}+p_i^*\times(A_i^{i+1}\cdot F_{i+1})+r_i^*\times(m_i\cdot\ddot{r}_{mi})+r_{pi}\times(\Pi_{mi}\cdot\ddot{r}_{mi})+(\tau_i+T_i)\cdot\dot{\omega}_i+$$
$$+\omega_i\times((\tau_i+T_i)\cdot\omega_i)+M_{pi}^{\mathrm{v}}+M_{pi}^{\omega}+M_{Li},\ M_{n+1}=0,\ i=\overline{n,1};$$

where $\delta_i=\begin{bmatrix}-(\omega_{i(2)}^2+\omega_{i(3)}^2) & \omega_{i(1)}\cdot\omega_{i(2)}-\dot{\omega}_{i(3)} & \omega_{i(1)}\cdot\omega_{i(3)}+\dot{\omega}_{i(2)}\\ \omega_{i(1)}\cdot\omega_{i(2)}+\dot{\omega}_{i(3)} & -(\omega_{i(1)}^2+\omega_{i(3)}^2) & \omega_{i(2)}\cdot\omega_{i(3)}-\dot{\omega}_{i(1)}\\ \omega_{i(1)}\cdot\omega_{i(3)}-\dot{\omega}_{i(2)} & \omega_{i(2)}\cdot\omega_{i(3)}+\dot{\omega}_{i(1)} & -(\omega_{i(1)}^2+\omega_{i(2)}^2)\end{bmatrix}$, in matrix δ_i lower index indicates number of element in respective vectors; $\omega_i,\dot{\omega}_i\in R^3$ – angular velocity and angular acceleration of link *i*, respectively; v_i - linear velocity of MM link *i*; $\omega_0,\dot{\omega}_0\in R^3$ – angular velocity and angular acceleration of base of MM, respectively; v_{Ai} - linear velocity of center of size of MM link *i*; v_i - linear velocity of MM link *i*; v_0 - linear velocity of MM base; $\ddot{P}_{UV}$ - linear acceleration of MM base; v_{Li} and v_{pi} - longitudinal and transverse components of v_i, respectively; ω_{Li} and ω_{pi} - longitudinal and transverse components of ω_i, respectively; $\Pi_1=0.1$ kg, $\Pi_2=\Pi_3=1.075$ kg - added masses of fluid attached to relevant link; $\ddot{r}_{mi}$ – linear acceleration of center of mass of link *i*; p_i^* - vector defining position of joint *i*+1 relative to joint *i*; r_{pi} - vector defining position of center of added mass of fluid Π_i relative to joint *i*; r_i^* - vector defining position of center of mass of link relative to joint *i* ($|r_1^*|$ = 0.025 m, $|r_2^*|=|r_3^*|=0.25$ m); $e_i=(0\ 0\ 1)^T$ – vector directed along axis of joint *i*; $F_i, M_i\in R^3$ – forces and moments which arises in joint *i*, respectively; $\eta=1.3*10^{-3}$ - viscosity of water; $k_{Li}, k_{pi}, k_{pi}^*, k_{Li}^*$ - viscous friction coefficients; $k_{L2}=k_{p2}=k_{p2}^*=k_{L2}^*=k_{L3}=k_{p3}=k_{p3}^*=k_{L3}^*=1$; K_{Ai} - parameter that depends of $|\mathrm{v}_{Ai}|$ and angle ψ_i, $K_{A2}=\sin\psi_2$, $K_{A3}=\sin\psi_3$; $T_{1_{11}}=1*10^{-4}$, $T_{1_{22}}=T_{1_{33}}=3*10^{-5}$, $T_{2_{11}}=T_{3_{11}}=1.4*10^{-3}$, $T_{2_{22}}=T_{2_{33}}=T_{3_{22}}=T_{3_{33}}=2.6*10^{-2}$ - diagonal elements of inertia tensor of fluid masses attached to relevant MM links; A_i^{i-1} - direction cosine matrix for considered kinematic scheme of MM (see Fig. 4)

$$A_2^1 = \begin{bmatrix} \cos q_1 & \sin q_1 & 0 \\ 0 & 0 & 1 \\ \sin q_1 & -\cos q_1 & 0 \end{bmatrix}, \quad A_3^2 = \begin{bmatrix} \cos q_2 & \sin q_2 & 0 \\ -\sin q_2 & \cos q_2 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \text{ where } A_{i-1}^i = (A_i^{i-1})^T .$$

Shall assume that CS of electric actuators of every MM degree of freedom have devices of adaptive correction [14] which provide dynamic precision and invariability of actuators work quality to intercoupling effects between all MM degrees of freedom. In result transfer functions of corrected electric actuators of every MM degree of freedom are

$$W_{\ddot{\imath}}(s) = \frac{q_i(s)}{q_i^*(s)} = \frac{k_{\ddot{\imath}}}{(T_1 s + 1)s}$$

at any lows of changes of MM generalized coordinates in process of MM movement. Where $k_n = \dfrac{1}{i_p k_\omega}$, $T_1 = \dfrac{R_a J}{k_m k_\omega}$, R_a = 0.2 Ohm - ohmic resistance; k_ω = 0.02 Vs - back emf constant; k_m = 0.02 Nm/A - torque constant; $J = 10^{-4}$ Kgm^2 - moment of inertia of motor spindle and reductor; i_p = 100 - reductor transmission ratio.

Mathematical modeling was performed for investigation of underwater MM work with synthesized CS (see Fig. 3). MM effector moved in horizontal plane along trajectory described by equation $(z = g_z(y) = \text{const})$

$$x = 0.3\sin(7y) + 0.1,$$

when $y(t)$ was formed by formula

$$\dot{y} = \frac{v(t)}{\sqrt{(1 + (2.1\cos(7y))^2)}},$$

received by formula (1). Initial point of MM effector moving trajectory has coordinates: $y_0 = 0$; $x_0 = 0.1$; $z_0 = 1$.

Processes of changes of x_k (t), y_k (t), z_k (t) and MM deviation from given trajectory ε_n (t) with using of synthesized system are shown on Fig 5. Also results of modeling (deviation ε_n (t)) without using of synthesized system are shown on Fig 6. From these figures it can be seen that synthesized CS allows 60 times increase accuracy of movement of underwater MM effector.

Conclusion

In this work method of synthesis of system of automatic correction of program trajectory of motion of MM installed on UV was proposed. Said CS allows performing manipulation operations with high accuracy at UV hang mode near object of work even at unintended displacements of UV from initial position. Using of synthesized system is assumed with systems of automatic stabilization of UV in desirable point of space.

Automatic correction is based on information about actual angular and linear displacements of UV from initial position and information about constantly varied MM configuration. Implementation of synthesized system is not difficult.

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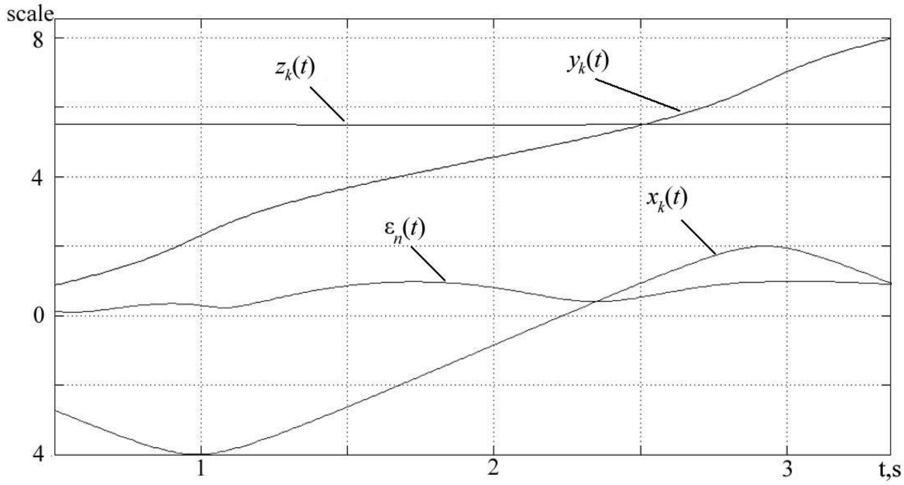

$y_k(t)$ = scale· 0.1 m; $x_k(t)$ = scale· 0.1 m; $z_k(t)$ = scale· 0.1 m; $\varepsilon_n(t)$ = scale · 0.002 m.
Fig. 5. Processes of changes of $y_k(t)$, $x_k(t)$, $z_k(t)$ and $\varepsilon_n(t)$ in synthesized system.

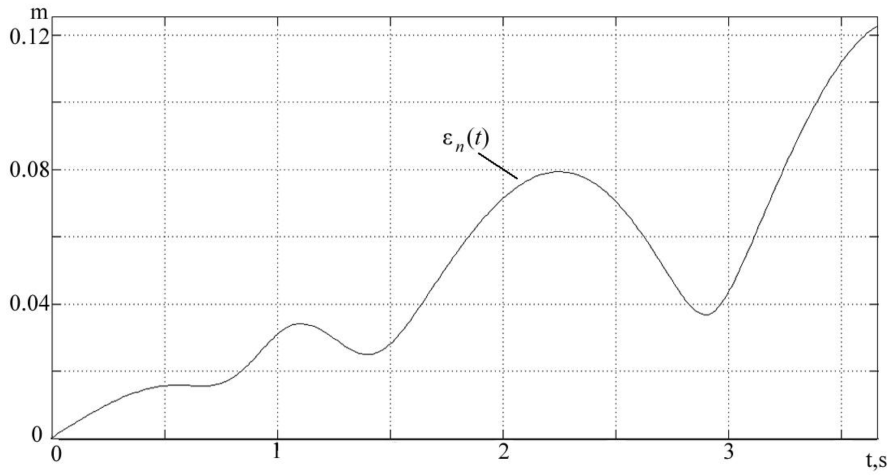

Fig. 6. Processes of changes of MM effector deviation $\varepsilon_n(t)$.

References

[1] V.F. Filaretov, D.A. Yukhimets, The Synthesis of System for Automatic Formation of Underwater Vehicle's Velocity, Proc. of the 20th International DAAAM Symposium, Katalinic, B. (Ed.), 25-28th November 2009, Vienna, Austria, pp. 1155-1156.

[2] V.F. Filaretov, D.A.Yukhimets, Synthesis Method of Control System for Spatial motion of Autonomous Underwater Vehicle, Int. Journal of Industrial Engineering and Management. Vol.3. No 3. 2012, pp. 133-141.

[3] V.F. Filaretov, Yu.K. Alekseev, A.V. Lebedev, Control system of underwater vehicle / Edited by V.F. Filaretov - M.: Krugliy god, 2001. 288 p. (В.Ф. Филаретов, Ю.К. Алексеев, А.В. Лебедев, Системы управления подводными роботами / Под ред. В.Ф. Филаретова. - М.: Круглый год, 2001. 288 с.).

[4] T.W. McLain, S.M. Rock, M.J. Lee, Experiments in the coordinated control of an underwater arm/vehicle system. Autonomous Robots, vol. 3, 1996. no. 2-3, pp. 213–232.

[5] V.F. Filaretov, A.V. Lebedev, D.A. Yukhimets, Devices and control systems of underwater robots.- M.: Nauka, 2005. 270 p. (В.Ф. Филаретов, А.В. Лебедев, Д.А. Юхимец, Устройства и системы управления подводных роботов. - М.: Наука, 2005. 270 с.).

[6] V.F. Filaretov, D.A. Yukhimets, Synthesis of a System of Automatic Calculation of Program Signals for Controlling Motion of an Underwater Vehicle along a Complex Spatial Trajectory. Journal of Computer and Systems Sciences International, 2010, Vol. 49, No. 1, pp. 96–104.

[7] J. Horgan, D. Toal, Computer vision applications in the navigation of unmanned underwater vehicles // Underwater Vehicles. In-Tech. 2009. 582 p.

[8] R. Eustice, O. Pizarro, Hanumant Singh Visually augmented navigation for autonomous underwater vehicles // IEEE Journal oceanic engineering. 2009. 1-18 p.
[9] E. Hinüber, New approaches in high-performance navigation solutions for AUVs and ROVs / iMAR. www.imar-navigation.de. 2010.
[10] V. Filaretov, A. Zhirabok, A. Zuev, A. Protcenko, The new approach for synthesis of diagnostic system for navigation sensors of underwater vehicles, Procedia Engineering, 69, 2014, P. 822-829.
[11] G.O. Fridlender, M.S. Kozlov, Aeronautical gyroscopic instruments. M. Oborongiz 1961. 390p. (Г.О. Фридлендер, М.С. Козлов, Авиационные гироскопические приборы. М. Оборонгиз 1961г., 390с.).
[12] K.S.Fu, R.C. Gonzalez, C.S.G. Lee, Robotics: control, sensing, vision and intelligence. McGraw-Hill,1987. 580p.
[13] G. Korn, T. Korn, Mathematical Handbook for Scientists and Engineers. M., 1973. 832 p. (Г. Корн, Т. Корн, Справочник по математике для научных работников и инженеров. М., 1973 г., 832 с.).
[14] V.F. Filaretov, Self-tuning control systems of manipulators actuators. Vladivostok: FESTU. 2000. - 304 p. (В.Ф. Филаретов, Самонастраивающиеся системы управления приводами манипуляторов. Владивосток: Изд-во ДВГТУ. 2000. - 304 с.).