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IMPROVEMENT OF THE MATHEMATICAL MODEL FOR SPATIAL MOTION OF A REMOTELY OPERATED UNDERWATER VEHICLE WITH TECHNOLOGICAL EQUIPMENT

УДОСКОНАЛЕННЯ МАТЕМАТИЧНОЇ МОДЕЛІ ПРОСТОРОВОГО РУХУ ТЕЛЕКЕРОВАНОГО ПІДВОДНОГО АПАРАТА З ТЕХНОЛОГІЧНИМ ОБЛАДНАННЯМ

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Abstract. Full-scale sea experiments of underwater vehicles and their automated control systems are an expensive and labor-intensive process. Moreover, execution of such experiments is always accompanied with the risk of damaging the components of an underwater vehicle or even injuring its crew. Thus, it is relevant to minimize the time of configuring automatic control systems of underwater vehicles through computer simulation. This paper considers advanced approaches to motion dynamics simulation for underwater vehicles with technological equipment. There is substantiated the necessity of developing a specialized mathematical model of a tethered remotely operated underwater vehicle with technological equipment. The proposed mathematical model accounts for an underwater vehicle that is organized according to the principle of separation of progressive motion of its hull and rotary motion of its technological equipment. The mathematical model of the rotary motion platform is designed; it considers the influence of disturbances arising from the technological equipment on the dynamics of its motion. The developed mathematical model will be used during the design and preliminary configuration of the automated control system for an underwater vehicle and its technological equipment.

Keywords: remotely operated underwater vehicle; technological equipment; manipulator; mathematical model.

Анотація. Запропоновано математичну модель підводного апарата, побудованого за принципом розділення поступального руху корпусу апарата та обертового руху його технологічного обладнання. Розроблено математичну модель платформи забезпечення обертового руху, яка враховує вплив збурень від технологічного обладнання на динаміку руху платформи.

Ключові слова: телекерований підводний апарат; технологічне обладнання; маніпулятор; математична модель.

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Problem statement. The rapid development of navigation, video and bathymetric surveying makes it possible to explore the underwater space, discover minerals, monitor ecological resources and provide technical support for water areas, install and repair underwater highways, and perform other types of underwater works with a high-quality documentation of the results. Typically, such works employ remotely operated underwater vehicles (ROVs) with a corresponding set of technological equipment (TE) (video cameras, manipulators, sonars, etc.). However, the ROVs available on the market do not meet the requirements for design modularity and multifunctionality and are thus ineffective for complex underwater works. In addition, automation of motion control for this type of vehicles and their technological equipment calls for the synthesis of multidimensional controllers with a complex structure and configuration.

Publication [1] proposes a brand new architectural and constructive type of ROVs. On the one hand, it meets the requirements of design multifunctionality and modularity; on the other hand, it provides better maneuvering than conventional ROVs and simplifies the procedure of motion control automation for the vehicle and its TE. These advantageous effects are achieved by separating the ROV structure into two platforms. One of them provides progressive motion of the ROV with TE underwater, while the other is designed to rotate the TE relative to the ROV's hull.

The use of numerous expensive elements and the complex structure of the ROV with motion separation as a control object pose a challenge for its production, basin and full-scale tests. Besides, in the course of conducting such works, there might occur various emergency situations leading to the damage or loss of the ROV's components or even injuries of crew members. These issues can be avoided by means of computer simulation of the controlled motion of the ROV and its TE in the process of development and production of the device, as well as during the development and implementation of the automatic control system for the ROV and TE motion. Hence, it is relevant to develop a mathematical model for the spatial motion of the ROV-TE complex.

Latest research and publications analysis. Scientific publications have extensively covered the topic of computer simulation of underwater vehicles equipped with manipulators. For instance, paper [7] proposes a mathematical model (MM) of a three-stage underwater manipulator. The motion dynamics equations applied to the model take into account the influence of rotary moments, hydrodynamic resistance and gravity. However, the model does not consider the impact of dynamics of the underwater vehicle on the state of the manipulator.

The MM described in [6] is devoid of the disadvantage mentioned above. In addition, the author of the publication uses open source software as a simulation environment; there, each component of the motion dynamics of the object is executed as a separate program module. Such a model does not provide for the influence of added masses and moments of inertia of water on the motion of the manipulator's joints, which leads to errors in the simulation results.

Paper [8] presents a MM of an autonomous underwater vehicle with a multi-stage manipulator. However, the manipulator movement here is only simulated in the underwater vehicle's center plane.

Publication [9] renders the development of a MM for the motion of the complex "autonomous underwater vehicle – underwater manipulator". The model accounts for the influence of added masses of water on the motion of the complex, as well as for the mutual influence of the manipulator and underwater vehicle on the dynamics of the complex. This model realizes the dynamics of the manipulator with two rotary degrees of freedom and does not take into account the effect of the load on the dynamics of the complex.

The MM of an underwater manipulator installed on the work-class ROV is presented in [4]. The publication deals with simulation of the motion of the manipulator and its influence on the ROV dynamics. However, the proposed MM does not account for the influence of the vehicle's tether on the process of its controlled motion.

The analysis of publications considering simulation of underwater complexes with manipulators foregrounds the need to develop a specialized mathematical model for the motion dynamics of a ROV with TE, which would take into account the structural features of this type of devices.

THE ARTICLE AIM is to develop a mathematical model for spatial motion of a remotely operated vehicle organized with separation of progressive and rotary motion and taking into account the impact of the vehicle's hull and TE on the process of its controlled motion.

Basic material. Fig. 1 displays the structure of a ROV with TE. Fig. 1 has the following indications: *1* — horizontal electromotive devices; *2* — progressive motion platform; *3* — tether; *4* — vertical electromotive device; *5* — technological equipment; *6* — rotary motion platform.

According to [2], the ROV motion is divided between two platforms. The progressive motion platform (PMP) with the help of horizontal and vertical electromotive devices (EMD) delivers the TE to the site of underwater works and provides for stabilization of its spatial position. The PMP is connected to the ROV carrier vessel with a tether (T), which is intended for power supply to the ROV and data exchange between the vehicle and the power and control station.

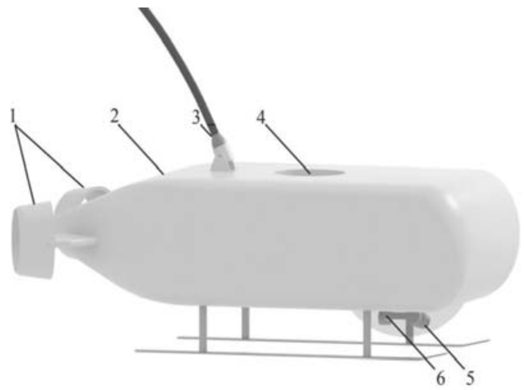


Fig. 1. Structure of a ROV with TE

The rotary motion platform (RMP) changes and maintains the position and spatial orientation of the TE by rotating it relative to the PMP. In this publication, the TE comprises a video camera. Since the TE is not supposed to interact with the underwater environment by design, I suggest placing it in a transparent hermetic capsule, which will eliminate the impact of hydrodynamic forces on the dynamics of the RMP-TE complex. Proceeding from the special features of the whole ROV-TE complex, it appears feasible for the mathematical model of its spatial motion to follow the structure demonstrated in Fig. 2.

Based on the vector of control actions $\vec{u}_P$, the MM of the propulsion and steering unit (PSU) aids in calculating the vectors of control forces $\vec{F}_P$ and moments $\vec{M}_P$, the impact of which makes the PMP's body move. The propulsion device comprises a model of the propeller, the thrust of which depends on the velocity of the PMP's progressive motion. The latter is taken into account as a feedback in the form of the vector $\vec{V}_{PMP}$.

The PMP motion is affected by the buoyant forces $\vec{F}_B$ and moments $\vec{M}_B$, as well as the gravity force $\vec{F}_G$. These forces and moments are calculated with the help of a mathematical model accounting for the buoyancy and gravity effects (BGE). Distribution of the forces and moments of buoyancy depends on the vector of the PMP's spatial orientation $\vec{H}_{PMP} = [\theta, \varphi, \psi]^T$, where θ, φ, ψ are the PMP's roll, course and trim angles, respectively. The MM of hydrodynamic effects (HE) takes into account the resistance of water to the PMP motion. The

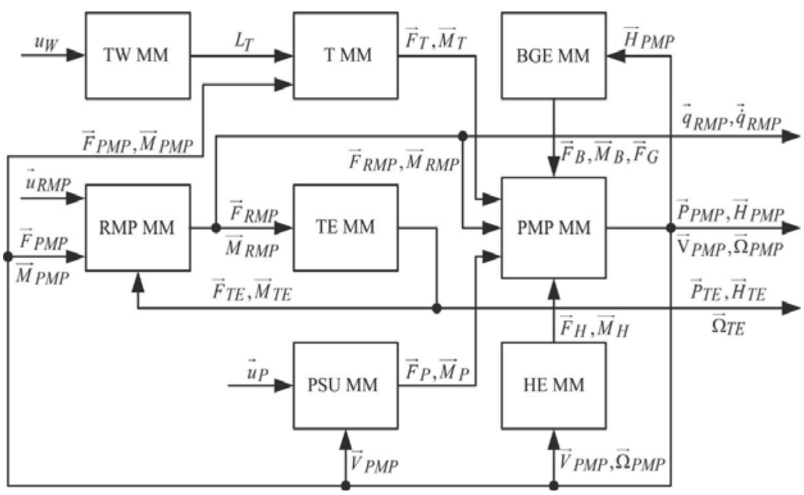


Fig. 2. Structure of the MM for spatial motion of a ROV with TE

hydrodynamic effects are indicated by the vectors of forces $\vec{F}_H$ and moments $\vec{M}_H$, which are quadratically dependent on the PMP's progressive $\vec{V}_{PMP}$ and rotary $\vec{\Omega}_{PMP}$ motion velocities. The MM of the tether is utilized to calculate the vectors of forces $\vec{F}_T$ and moments $\vec{M}_T$ of the tension at the tether's running end on the PMP motion. The length of the released part of the tether L_T is controlled by a tether winch (TW) via the signal u_W.

With regard to the vector of control actions $\vec{u}_{RMP}$ and the resultants of the PMP's forces $\vec{F}_{PMP}$ and moments $\vec{M}_{PMP}$, the MM of the RMP establishes the vectors of forces $\vec{F}_{RMP}$ and moments $\vec{M}_{RMP}$ that cause the TE motion relative to the PMP. The vectors of forces $\vec{F}_{TE}$ and moments $\vec{M}_{TE}$ calculated with the help of the MM of the TE affect the RMP motion dynamics. The following set is the output of the MM of the ROV with TE: vectors of position ($\vec{P}_{PMP}$, $\vec{P}_{TE}$), spatial orientation ($\vec{H}_{PMP}$, $\vec{H}_{TE}$), and rotary motion velocities ($\vec{\Omega}_{PMP}$, $\vec{\Omega}_{TE}$) of the ROV and the TE, respectively; vectors of rotation angle $\vec{q}_{RMP}$ and rotation rate $\dot{\vec{q}}_{RMP}$ of the RMP's rotating units; vector of velocities of the PMP's progressive motion $\vec{V}_{PMP}$.

The MM of the PMP implements the basic law of the ROV motion dynamics [3]:

$$\left.\begin{aligned} \frac{dV_{PMPa}}{dt} &= I_{PMP}^{-1}\left(T_{PMP} - KI_{PMP}V_{PMPa}\right); \\ \frac{dR_{PMP}}{dt} &= K_V\left(V_{PMPa} + V_s\right). \end{aligned}\right\}$$

In these equations, $V_{PMPa} = [v_{PMPxa}\ v_{PMPya}\ v_{PMPza}\ \omega_{PMPxa}\ \omega_{PMPya}\ \omega_{PMPza}]^T$ is the matrix of projections of the PMP's progressive and rotary motion velocities on the axis of the bound coordinate system (BCS); $R_{PMP} = [\vec{P}_{PMP}\ \vec{H}_{PMP}]^T$ is the matrix of the PMP's progressive and angular coordinates in the reference coordinate system (RCS); $T_{PMP} = [\vec{F}_{PMP}\ \vec{M}_{PMP}]^T$ is the matrix of forces and moments affecting the PMP motion dynamics; I_{PMP} is the matrix of the PMP's empty and attached masses; V_S is the matrix of sea current velocities expressed in the BCS; K_V is the coupling matrix for the PMP's position and speed kinematic parameters; K is the matrix taking into account the frame motion for the BCS derivation.

The matrix $I_{PMP} = M + \Lambda$ is determined by the M matrix of the masses and moments of inertia of the PMP and the Λ matrix of the added masses and moments of inertia of water:

$$M = diag\{m, m, m, j_x, j_y, j_z\};$$
$$\Lambda = \begin{bmatrix} \lambda_{11} & \cdots & \lambda_{16} \\ \vdots & \ddots & \vdots \\ \lambda_{61} & \cdots & \lambda_{66} \end{bmatrix}. \tag{1}$$

In equation (1), m is the PMP's mass; j_x, j_y, j_z are the PMP's moments of inertia; λ_{ij} is the added mass of water, $i = 1\ldots6$, $j = 1\ldots6$. The K matrix has the following form:

$$K = \begin{bmatrix} 0 & -\omega_{PMPza} & \omega_{PMPya} & 0 & 0 & 0 \\ \omega_{PMPza} & 0 & -\omega_{PMPxa} & 0 & 0 & 0 \\ -\omega_{PMPya} & \omega_{PMPxa} & 0 & 0 & 0 & 0 \\ 0 & -v_{PMPza} & v_{PMPya} & 0 & -\omega_{PMPza} & \omega_{PMPya} \\ v_{PMPza} & 0 & -v_{PMPxa} & \omega_{PMPza} & 0 & -\omega_{PMPxa} \\ -v_{PMPya} & v_{PMPxa} & 0 & -\omega_{PMPya} & \omega_{PMPxa} & 0 \end{bmatrix}.$$

The coupling matrix for the PMP's position and speed kinematic parameters has the following form:

$$K_V = \begin{bmatrix} K_v & 0_{3\times3} \\ 0_{3\times3} & K_\omega \end{bmatrix}. \tag{2}$$

For equation (2), I propose the following K_v coupling matrix between the BCS and RCS:

$$K_v = \begin{bmatrix} \cos\varphi\cos\psi & \begin{matrix}(\sin\varphi\sin\theta - \\ -\cos\varphi\sin\psi\cos\theta)\end{matrix} & \begin{matrix}(\cos\varphi\sin\psi\sin\theta + \\ +\sin\varphi\cos\theta)\end{matrix} \\ \sin\psi & \cos\psi\cos\theta & -\cos\psi\sin\theta \\ -\sin\varphi\cos\psi & \begin{matrix}(\sin\varphi\sin\psi\cos\theta + \\ +\cos\varphi\sin\theta)\end{matrix} & \begin{matrix}(\cos\varphi\cos\theta - \\ -\sin\varphi\sin\psi\sin\theta)\end{matrix} \end{bmatrix}. \tag{3}$$

The K_ω kinematic coupling matrix between rotary motion and (2) has the following form:

$$K_\omega = \begin{bmatrix} 1 & \sin\psi & 0 \\ 0 & \cos\psi\cos\theta & \sin\theta \\ 0 & -\cos\psi\sin\theta & \cos\theta \end{bmatrix}^{-1}$$

The resultant of the forces and moments affecting the PMP motion is calculated as follows:

$$T_{PMP} = T_H + T_{GB} + T_P + T_T + T_{RMP}, \tag{4}$$

where $T_H = \left[\vec{F}_H \quad \vec{M}_H\right]^T$ is the matrix of hydrodynamic forces and moments; $T_{GB} = \left[\vec{F}_{GB} \quad \vec{M}_{GB}\right]^T$ is the matrix of forces and moments of gravity and buoyancy of the PMP's body; $T_P = \left[\vec{F}_P \quad \vec{M}_P\right]^T$ is the matrix of forces and moments generated by the PMP's propulsion and steering unit; $T_T = \left[\vec{F}_T \quad \vec{M}_T\right]^T$ is the matrix of forces and moments of the tether tension; $T_{RMP} = \left[\vec{F}_{RMP} \quad \vec{M}_{RMP}\right]^T$ is the matrix of forces and moments exerted by the RMP at its mounting point.

Let us further elaborate on each component of expression (4) separately. The matrix of hydrodynamic effects has the following form:

$$T_H = \begin{bmatrix} \vec{F}_H \\ \vec{M}_H \end{bmatrix} = \begin{bmatrix} -0,5k_{Fx}\rho S_x v_{PMPxa}^2 \\ -0,5k_{Fy}\rho S_y v_{PMPya}^2 \\ -0,5k_{Fz}\rho S_z v_{PMPza}^2 \\ -0,5k_{Mx}\rho V \omega_{PMPxa}^2 \\ -0,5k_{My}\rho V \omega_{PMPya}^2 \\ -0,5k_{Mz}\rho V \omega_{PMPza}^2 \end{bmatrix},$$

where k_{Fx}, k_{Fy}, k_{Fz} are the coefficients of projections of hydrodynamic forces on the BCS axes; k_{Mx}, k_{My}, k_{Mz} are the coefficients of projections of hydrodynamic moments on the BCS axes; S_x, S_y, S_z are the reference areas of the PMP's body; ρ is the water density; V is the PMP's deadweight.

The MM of the BGE utilizes the following expression:

$$T_{GB} = \begin{bmatrix} F_{GBx} \\ F_{GBy} \\ F_{GBz} \\ M_{GBx} \\ M_{GBy} \\ M_{GBz} \end{bmatrix} = \begin{bmatrix} (F_B - F_G)\sin\psi \\ (F_B - F_G)\cos\psi\cos\theta \\ -(F_B - F_G)\cos\psi\sin\theta \\ -F_B z_B \cos\psi\cos\theta - F_B y_B \cos\psi\sin\theta \\ F_B x_B \cos\psi\sin\theta + F_B z_B \sin\psi \\ F_B x_B \cos\psi\cos\theta - F_B y_B \sin\psi \end{bmatrix},$$

where $F_B = \rho\Omega g$ is the buoyancy force module; $F_G = mg$ is the gravity force module; x_B, y_B, z_B are the coordinates of the point of exertion of the buoyancy force; Ω is the ROV's volume submerged in water; ρ is the water density; g is the acceleration of gravity.

The dynamics of the PMP's PSU is calculated with the help of the following correlation:

$$T_P = \left[\vec{F}_P \quad \vec{M}_P\right]^T = \sum_i T_i,\ i = 1, 2, \ldots, I;$$

$$T_i = \left[\vec{F}_i \quad \vec{M}_i\right]^T; \vec{F}_i = F_i \hat{d}_i; \vec{M}_i = \vec{r}_i \times \vec{F}_i,$$

where T_i is the matrix of propulsion forces and moments generated by the PSU's EMDs; I is the number of EMDs comprising the PSU; F_i is the thrust created by the PSU; $\vec{F}_i$ stands for the projections of the thrust created by the PSU on the BCS axes of the PMP; $\hat{d}_i$ stands for the coordinates of the vector characterizing the direction of exertion of the EMD thrust; $\vec{r}_i$ stands for the EMD's coordinates in the BCS of the PMP; $\vec{M}_i$ stands for the projections of the moment generated by the EMDs onto the BCS axes of the PMP.

In this publication, I propose to use DC motors with a propeller as the EMDs, since these devices are easy to manufacture and handle, and their dynamic properties are well-known. The MM of the EMD based on an electric motor with a propeller is discussed in detail in paper [3].

The MM of the tether is intended for calculation of the TT matrix of forces and moments of the tension of tether's running end. The tether is divided into n elements connected via $n-1$ links. The dynamics of a tether's element is expressed as follows:

$$\left.\begin{aligned} &\vec{F}_i = \vec{f}\left(\vec{r}_{i-1}, \vec{r}_i, \vec{r}_{i+1}, \frac{d\vec{r}_i}{dt}, L_T\right); \\ &m\ddot{\vec{r}}_i = \vec{F}_i, \end{aligned}\right\} \tag{5}$$

where $\vec{F}_i$ is the vector of the resultant force acting on the tether's elementary section, $i = 1, 2, \ldots, n$; $\vec{r}_i$ stands for the coordinates of the tether's elementary section; L_T is the length of the released part of the tether.

It is proposed to establish the components of expression (5) using the method of automatic control of the axial motion of the tether's elements [2]. The components of the T_T matrix are defined from the following expression:

$$T_T = \begin{bmatrix} \vec{F}_T \\ \vec{M}_T \end{bmatrix} = \begin{bmatrix} -\vec{F}_n \\ -\vec{r}_T \times \vec{F}_n \end{bmatrix},$$

where $\vec{r}_T$ stands for the coordinates of the point of attachment of tether's running end.

Release and collection of the tether are simulated on the basis of the MM for the TW dynamics, which can be represented in the reduced form as the following system [3]:

$$\left.\begin{aligned} &M_{EM} = f\ \ u_W, \omega\ ; \\ &\dot{\omega} = f\ \ M_{EM}, M_L\ ; \quad M_L = RF_1; \\ &\dot{L}_T = R\omega, \end{aligned}\right\}$$

where u_W is the control signal of the TW's drive, M_{EM} is the driving torque of the TW's motor, ω is the rotational speed of the TW's barrel, M_L is the braking torque on the TW's barrel, R is the radius of the TW's barrel; F_1 is the module of the tether tension force at its inboard end.

The RMP structure is rendered through the formula "RPPRPPR", where R stands for the link that performs rotary motion, whereas P stands for the link that performs progressive motion. The lengths of the progressive links remain unchanged, so the RMP can be regarded as a three-stage manipulator with TE included to its operating device. Fig. 3 presents the general view of a RMP with TE installed on its operating device.

It is proposed to describe the initial position of the manipulator's joints with the use of the *DH* modified matrix of the Denavit-Hartenberg parameters [5]. Each matrix row is a set of parameters for a particular manipulator's joint: $DH_i = [\alpha_i\ \beta_i\ d_i\ a_i]$, where d_i is the length of the link on the $O_{i-1}Y_{i-1}$ axis of the previous joint; a_i is the length of the link on the $O_{i-1}X_{i-1}$ axis of the previous joint; α_i is the angle of rotation of the link's coordinate system around the $O_{i-1}Z_{i-1}$ axis of the previous joint; β_i is the angle of rotation of the link's coordinate system around the O_iY_i axis; $i = 1, 2, \ldots, L$; L is the number of the RMP's rotary joints. The BCS of the PMP is regarded as an input for the coordinate system of the RMP's first joint. The matrix of the Denavit-Hartenberg parameters intended for description of the RMP is presented in Table 1.

The spatial positions and orientation of the RMP's joints are determined by the elements of the matrix of positions of their shafts $q = [q_1 \ldots q_L]^T$.

The position and spatial orientation of the TE shall be described with the following matrix:

$$A_{TE} = \begin{bmatrix} K_{TE} & \vec{P}_{TE} \\ 0_{1\times3} & 1 \end{bmatrix} = A_{PMP}\prod_{i=1}^{L} A_i, \qquad (6)$$

where K_{TE} is the 3×3 matrix rendering the spatial orientation of the TE; A_{PMP} is the matrix containing the position and spatial orientation of the PMP; A_i is the matrix containing the position and spatial orientation of the RMP.

The A_{PMP} matrix in expression (6) has the following form:

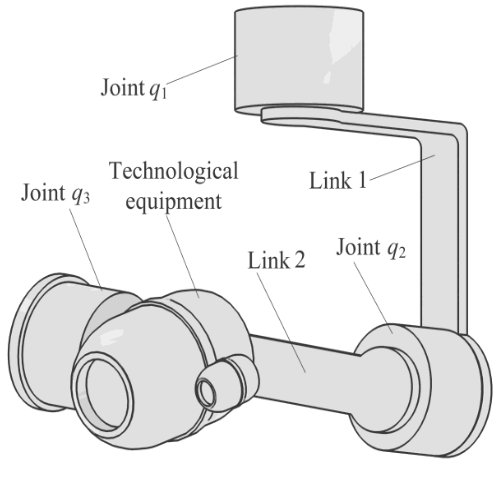
$$A_{PMP} = \begin{bmatrix} K_v & \vec{P}_{PMP} \\ 0_{1\times3} & 1 \end{bmatrix}.$$

The A_i matrix depends on the Denavit-Hartenberg parameters and the position of the shaft of the joint's motor [5]:

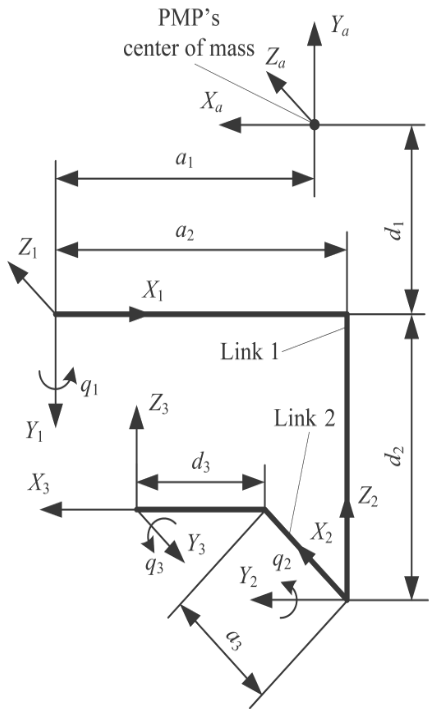
$$A_i = \begin{bmatrix} \cos(\beta_i + q_i)\cos\alpha_i & -\sin\alpha_i & \sin(\beta_i + q_i)\cos\alpha_i & a_i \\ \cos(\beta_i + q_i)\sin\alpha_i & \cos\alpha_i & \sin(\beta_i + q_i)\sin\alpha_i & d_i \\ -\sin(\beta_i + q_i) & 0 & \cos(\beta_i + q_i) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Kinematics of the RMP shall be established with the aid of expression (6):

$$R_{TE}(q) = \begin{bmatrix} \vec{P}_{TE} \\ rotMat2euler(K_{TE}) \end{bmatrix},$$



a



b

Fig. 3. RMP with TE: *a* — general view; *b* — kinematic model

Table 1. Matrix of the Denavit-Hartenberg parameters for the RMP

Parameter / Joint no.	α, °	β, °	*d*, m	*a*, m
1	180	0	d_1	a_1
2	90	–90	d_2	a_2
3	90	0	d_3	a_3

where *rotMat2euler* is the function generating the vector of the TE's Euler angles $\vec{H}_{TE} = [\theta_{TE}, \varphi_{TE}, \psi_{TE}]^T$ from the K_{TE} matrix of spatial orientation of the TE [5].

The basic law of the RMP dynamics shall be described as follows:

$$\left.\begin{aligned} \frac{d^2q}{dt^2} &= I_{RMP}^{-1} \ T_J - T_C - T_F - T_G - T_{BE} \ ; \\ \frac{dR_{TE}}{dt} &= J\frac{dq}{dt}, \end{aligned}\right\}$$

where I_{RMP} is the matrix of moments of inertia of the RMP's joints; T_J is the matrix of rotary moments of the motors of the RMP's joints; T_C is the matrix of centripetal and Coriolis forces; T_F is the matrix accounting for the effect of viscous and dry friction; T_G is the matrix that takes into account the effect of gravity; T_{BE} is the matrix that accounts for the effect of the TE and the PMP; R_{TE} is the matrix of the TE's progressive and angular coordinates in the RCS of the PMP; J is the matrix resulting from differentiation of the expressions for the direct law of RMP kinematics with respect to the elements of the q matrix.

DC motors are suggested for use as the motors of the RMP's rotary joints as well. In this case, the T_J matrix can be obtained with the help of the EMD model [3] excluding the effect of the propeller on the dynamics of the motor.

The T_C, T_F, T_G matrices shall be formed using the Newtonian-Euler recursive method [5]. Its advantage resides in establishing the matrix of forces and moments of the RPM affecting the PMP dynamics in the process of calculation: $T_{RMP} = \left[\vec{F}_{RMP} \quad \vec{M}_{RMP}\right]^T$.

The matrix of the effect of the TE and the PMP is rendered via the expression below:

$$T_{BE} = J^T(T_{TE} + K_{TE}T_{PMP})$$

with $T_{TE} = \left[\vec{F}_{TE} \quad \vec{M}_{TE}\right]^T$ being the matrix of forces and moments generated by the TE.

The K_{TE} matrix has the following form:

$$K_{TE} = \begin{bmatrix} K_{vTE} & t_{TE}K_{vTE} \\ 0_{3\times3} & K_{vTE} \end{bmatrix}^T. \qquad (7)$$

Within expression (7), the K_{vTE} matrix is established by replacing the coordinates of the PMP's spatial orientation $\vec{H}_{PMP} = [\theta \ \varphi \ \psi]^T$ in expression (3) with the coordinates of the TE's spatial orientation $\vec{H}_{TE}$. The tTE matrix in expression (7) has the following form:

$$t_E = \begin{bmatrix} 0 & -z_{TE} & y_{TE} \\ z_{TE} & 0 & -x_{TE} \\ -y_{TE} & x_{TE} & 0 \end{bmatrix},$$

where x_{TE}, y_{TE}, z_{TE} are the coordinates of the TE's current position in the RCS of the PMP.

The PMP dynamics is affected by the gravity force of TE, which does not generate any moments. Thus, the T_{TE} matrix shall be presented as follows:

$$T_{TE} = \left[\vec{F}_{TE} \quad \vec{M}_{TE}\right]^T = [0 \ m_{TE}g \ 0 \ 0 \ 0 \ 0]^T$$

where m_{TE} is the mass of the TE.

The applicability of the MM under development has been tested in MATLAB Simulink. The parameters of the PMP are listed in Table 2, while those of the RMP are given in Table 3.

First, let us consider the case when the TE's course angle changes at linear motion of the vehicle with no impact of external disturbances, that is, the roll and trim angles of the vehicle are equal to zero and do not change over time. The RMP control action shall be formed according to the dependence $q = [(\pi/6)\sin(0.5t) \ 0 \ 0]^T$, where t is the instantaneous value of simulation time. The PMP control action has the following form: $u_{PMP} = [u_l \ u_r \ u_v]^T$, where u_l, u_r, u_v are the control signals sent to the horizontal left-hand, right-hand and vertical EMDs. Simulation assumes that $u_{PMP} = [0.2 \ -0.2 \ 0]^T$. The simulation results are presented in Fig. 4.

The TE's course angle φTE (Fig. 4, *a*) varies according to the sinusoidal law, while the roll (θ_{TE}) and trim

Table 2. Parameters of the mathematical model of the PMP

Parameter name	Value
Body shape: length, m height, m width, m	Triple ellipsoid 1 0.35 0.65
Coordinates of the point of exertion of the buoyancy force in the BCS, m	{0.25, 0.1, 0}
Coordinates of the point of attachment of the tether in the BCS, m	{–0.25, 0.15, 0}
EMD coordinates in the BCS: left-hand, m right-hand, m vertical, m	 {–0.3, 0, –0.3} {–0.3, 0, 0.3} {0, 0, 0.2}
Weight, kg	120
Deadweight, m^3	0.12
Tether length, m	100
EMD capacity, W	500

Table 3. Parameters of the mathematical model of the RMP

Parameter name	Value
Denavit-Hartenberg parameters: [d_1; a_1], m [d_2; a_2], m [d_3; a_3], m	 [–0.25; 0.25] [0.3; 0.3] [0.15; 0.15]
TE shape:	Cylinder
height, m	0.15
base radius, m	0.06
TE weight, kg	3
Weight of the joint's motor, kg	5
Capacity of the joint's motor, W	100

(ψ_{TE}) angles remain unchanged, since the PMP is not tilted, which proves that the spatial orientation of technological equipment has been calculated correctly.

As the PMP is not tilted, the TE's progressive coordinates shall change according to the following law:

$$\vec{P}_{TE}(t)=\begin{bmatrix} x_{PMP}(t)+2x_{TE}(0)-\rho\cos(q_1(t)-\alpha_x) \\ y_{PMP}(t)+y_{TE}(0) \\ z_{PMP}(t)+2z_{TE}(0)-\rho\cos(q_1(t)-\alpha_z) \end{bmatrix},$$

where ρ is the length of the vector $\vec{P}_{TE}(0) = [x_{TE}(0)\ y_{TE}(0)\ z_{TE}(0)]^T$, which is directed from the origin of the BCS of the PMP to the point of initial location of the TE (identified via the Denavit-Hartenberg parameters); α_x is the angle between the projection of the $\vec{P}_{TE}(0)$ vector on the $O_AX_AZ_A$ plane and the O_AX_A axis of the BCS of the PMP; α_z is the angle between the projection of the $\vec{P}_{TE}(0)$ vector on the $O_AX_AZ_A$ plane and the O_AZ_A axis of the BCS of the PMP.

Fig. 4, *b* clearly indicates that the y_{TE} coordinate remains the same, while the x_{TE} and z_{TE} coordinates change according to the law given above, which testifies to the applicability of the mathematical model under consideration.

Let us now consider the case when the PMP is affected by the forces of tether disturbances (see Fig. 5) in the course of its motion.

These effects lead to the PMP tilting and, consequently, the change in the TE's trajectory. Fig. 6 shows the graphs rendering the change in the spatial orientation and position of the PMP and the TE. The PMP and RMP control actions are same as in the previous case.

The emergence of the PMP tilting causes a change in the TE's roll and trim angles according to the law which depends on the RMP control action. Moreover, the PMP tilting leads to a change in the amplitude of oscillations of x_{TE} and z_{TE}. In addition, the tether disturbances cause a change in the depth of submersion of the PMP and, as a result, the TE's vertical coordinate. Hence, the mathematical model can recreate the motion of the ROV and its TE along complex spatial trajectories.

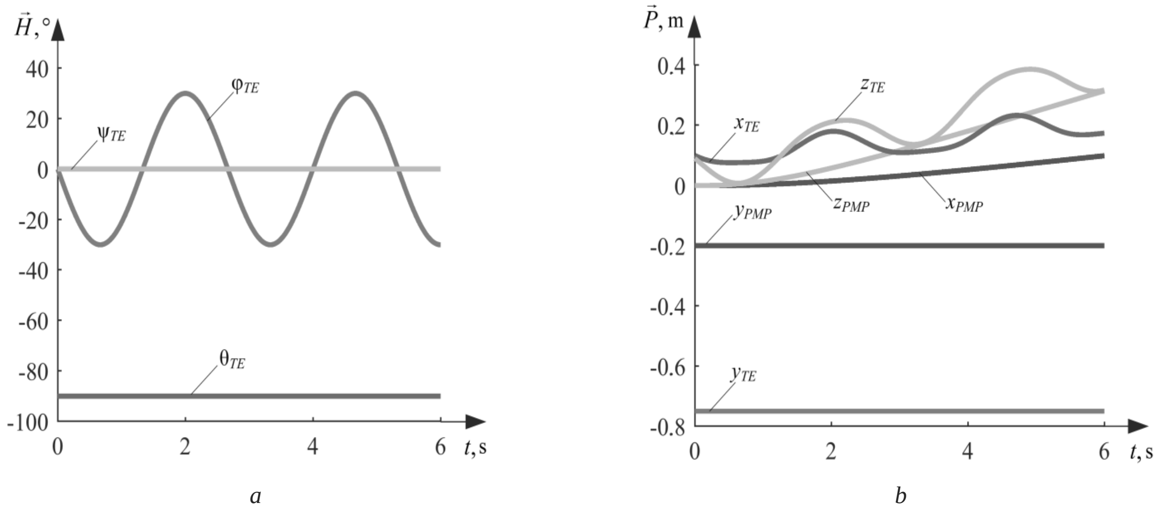


Fig. 4. Dependence of the TE's position on time provided the PMP is not tilted: *a* — Euler angles; *b* — progressive coordinates

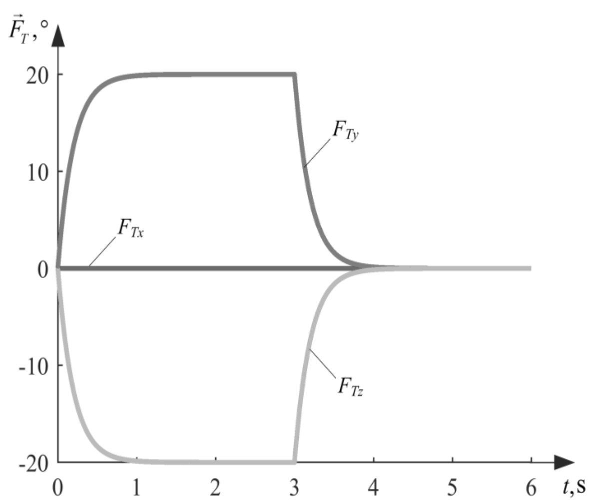


Fig. 5. Tether disturbances

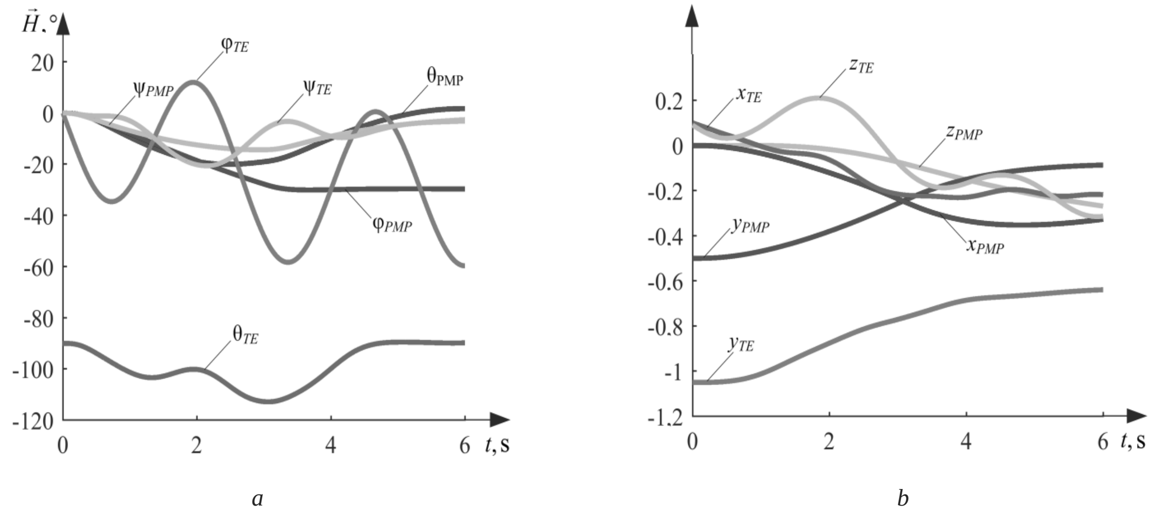


Fig. 6. Dependence of the TE's position on time provided the PMP is tilted: *a* — Euler angles; *b* — progressive coordinates

CONCLUSIONS. 1. There has been improved the mathematical model of a tethered ROV, which is organized by the principle of separation of progressive and rotary motion and takes into account the impact of technological equipment on the motion dynamics of the vehicle. It is proposed to apply the model for synthesis and study of automatic control systems for the vehicles of this type. 2. There has been developed a mathematical model of the platform for rotary motion of technological equipment relative to the ROV's hull. The platform is represented by a three-stage manipulator, each joint of which changes one of the coordinates of spatial orientation of the technological equipment. It is recommended to use the developed mathematical model as part of the mathematical model of the ROV to study its motion dynamics and synthesize appropriate automatic control systems.

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