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The New Strategy of Designing Tracking Control Systems for Dynamical Objects with Variable Parameters[1]

In this paper, the new strategy of controlling complicated dynamical objects with variable or unknown parameters during their movement along smooth spatial trajectories is proposed. The proposed strategy is based on correcting program signals that define the movement of this object depending on accurate dynamical-object movement. Using this strategy considers the variance of dynamical object parameters and increased accuracy of their movement when typical linear controllers are used. The simulations and experimental researches confirmed the workability and efficacy of the proposed strategy.

Keywords: *control theory, tracking systems, mobile robot control, accuracy, design systems, dynamic object, motion control systems*

1. Introduction

There are three basic strategies used for controlling different dynamical objects (DOs) in tracking mode: the feedback strategies [1], the invariance principle [2], and the strategy of joint nominal and local control. However, using these known strategies often does not solve the task of accuracy control by means of simple controllers for a new class of complex multiconnected systems with variable and unknown parameters (underwater vehicles and multilink manipulators).

The generalized structure diagram of a tracking system with n control channels and using of the feedback strategy is presented in Fig. 1, and the following notation is used in this diagram: DO is the dynamical object, MCU represents the main control units installed in each control channel, FBS represents the feedback sensors, and $X_B(t)$, $X^*(t)$, $\varepsilon(t)$, $u(t) \in R^n$, where $\alpha(t)$ is the vector of controlled coordinates, $X^*(t)$ is the vector of desired (program) values of these coordinates, $\varepsilon(t) = X^*(t) - X_B(t)$ is the vector of errors in corresponded control channels, and $u(t)$ is the vector of control signals. To reach the high control accuracy in the schema presented in Fig. 1, the controllers with transfer function $W_k(s)$ similar to $k/W_{ok}(s)$ should be entered in each control channel. Here $W_{ok}(s)$ is the transfer function of DO, k is the large gain, and s is the Laplace operator. However, the transfer function $k/W_{ok}(s)$ cannot be implemented, as all real DO has reduced frequency response, and larger values of k decreases the stability of the system. Furthermore, if the frequency and amplitude of $X^*(t)$, which approach harmonic signals, is increased, then the values $\varepsilon(t)$ increases as well while considering the limited bandwidth of DO even when adaptive controllers are used.

It can provide the robustness of quality parameters of system working by means of the invariance principle (two-channel control) [2]. The generalized diagram that implements this strategy is shown in Fig. 2. In this diagram, the ACU are the additional control units with transfer functions $W_{ak}(s) = 1/(W_{ok}(s)W_k(s))$ that enter in each con-

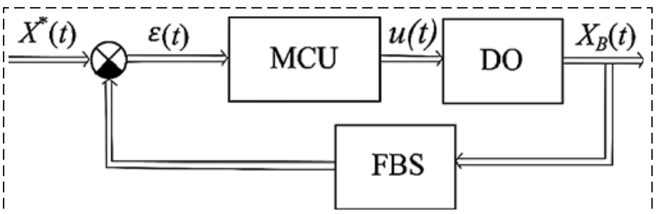

Fig. 1. The generalized structural diagram of the tracking system

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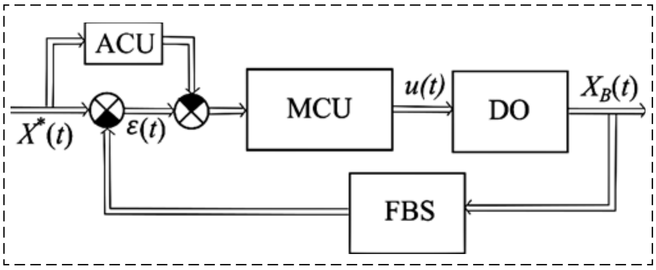

Fig. 2. The generalized diagram of implementing the invariance principle

trol channel. However, the transfer function $W_{ak}(s)$ cannot be implemented exactly because of the reason described earlier in the introduction. Thus, it is impossible to provide precise invariance of quality parameters to different external unknown and variable influences.

The third known strategy of local, global, and adaptive control [3, 4] can be used for controlling complex multiconnected DO (multilink manipulators and underwater vehicles) with variable and unknown parameters. The generalized schema of implementation of this strategy is presented in Fig. 3, where $U_g(t) \in R^n$ is the vector of global control.

The general idea of this strategy is to calculate the signal for movement of DO for each control channel (manipulator of underwater vehicle) at corresponding coordinates while considering its dynamic properties. It supposes that DO has nominal values of its parameters, that the restrictions of power of DO actuators are not considered, and that the arbitrary (unknown and unmeasured) external influences are presented. This control must provide the main trend of required movement of DO but signal $u(t)$, which forms by means of the first-control strategy [1], and the control must compensate for the inevitable errors due to accounting for its dynamic properties and unknown external influences. The MCU may also include the typical or adaptive controllers by considering the presence of unknown or variable parameters of DO.

A disadvantage of this strategy is the necessity to use complicated CS [5—9] that nevertheless cannot provide for the actuator restrictions in each control

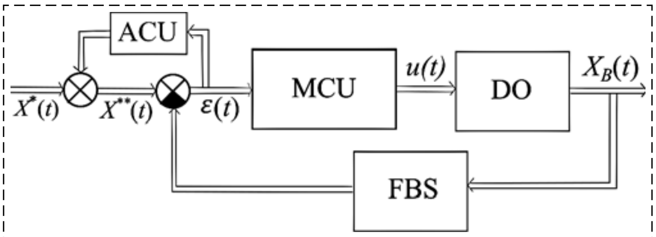

Fig. 3. The generalized schema of implementing this strategy

channel of DO. This can lead to control loss of this DO.

Therefore, the analysis above shows that there is no control strategy that easily creates implemented CS for high-accuracy control of complicated DO with variable and unknown parameters during its movement along arbitrary smooth spatial trajectories.

2. Task setting

In this paper, the following task is set and solved. It is necessary to develop the new control strategy for complicated nonlinear DO with variable and unknown parameters to provide high accuracy control by considering the restricted DO actuators by means of easily implemented CS. To develop the new synthesis methods, these CS that provide the deviation of DO from desired trajectories cannot exceed the allowable values.

This new strategy supposes not only the direct control of DO when it moves along desirable trajectories (it usually needs to use the differential equations instrument) but also the control of program signals coupled with simple tracking control systems installed in each control channel and providing only stability of the corresponding control loop. These CS must control the program signals that form such coordinates of the moving target points which ensure DO movement near all parts of the desirable trajectories with high accuracy even if large errors of tracking are present.

3. The description of movement of dynamic control object along spatial trajectory

The DO already has the typical (simple) CS as follows:

$$u(t) = F_u(\varepsilon(t), X^*(t)), \qquad (1)$$

which provide its stable movement along spatial trajectory. The vector $X^*(t)$ is formed in the global coordinate frame (GCF) by means of the following expression [10, 11]:

$$\dot{X}^*(t) = \begin{bmatrix} 1 \\ g'_y(x^*) \\ g'_z(x^*) \end{bmatrix} \Phi(x^*)v^* = f_v(x^*)v^*, \qquad (2)$$

where $\Phi(x^*) = (1 + (g'_y(x^*))^2 + (g'_z(x^*))^2)^{-1/2}$; $g'_y(x^*) = \dfrac{\partial g_y(x^*)}{\partial x^*}$, $g'_z(x^*) = \dfrac{\partial g_z(x^*)}{\partial x^*}$; $g_y(x^*)$, $g_z(x^*)$

are the functions describing the desired trajectory of DO movement in vertical and horizontal plans, respectively; v^* is the program velocity of DO movement along this trajectory.

The values of elements of vector $\varepsilon(t)$ depend on the curvature of current path of trajectory, velocity of Do movement along this trajectory, used CS, and vector P of the variable parameters of DO

$$\varepsilon(t) = F_\varepsilon(X^*(t),\ F_u(\cdot),\ P). \qquad (3)$$

If DO moves along the curvilinear trajectory and $\varepsilon(t) \neq 0$, then vector $\varepsilon_n(t) = F_n(X(t), g_y(\cdot), g_z(\cdot), \varepsilon(t)) \neq \neq 0 \in R^n$ always arises (see Fig. 4). This vector defines the deviation of DO from the trajectory and always satisfies the following inequality:

$$0 \leqslant \|\varepsilon_n\| \leqslant \|\varepsilon\|. \qquad (4)$$

If value of vector P is variable and control law $F_u(\cdot)$ is unchanged, then value $\|\varepsilon_n\|$ can be decreased by means of changing of coordinates of vector $X^*(t)$. Expression (2) shows that it can be possible by means of decreasing the value v^* on the part of the trajectory having a large curvature. However, it is undesirable if actuators of DO have a reserve of power to provide the high-speed movement.

In accordance with task setting described above and using typical tracking CS (TCS) described by (1) and vector $X^*(t)$ described by (2), we develop the new control strategy for DO on the basis of forming a program signal of its movement that allows movement along all parts of trajectory based on the

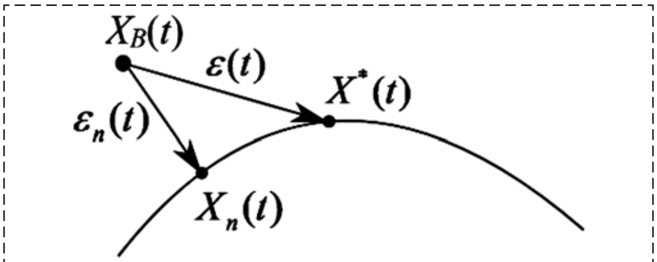

Fig. 4. The vectors of dynamic errors and deviation

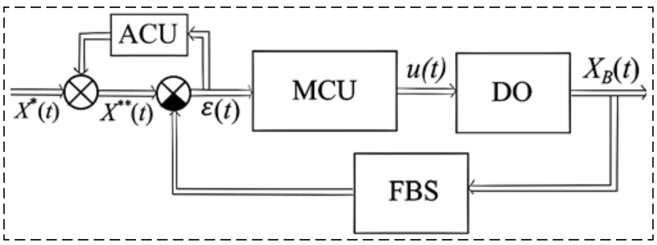

Fig. 5. The generalized diagram of CS DO that implements the new control strategy

saturation of DO actuators and satisfying the following condition:

$$\|\varepsilon_n(t)\| \leqslant \varepsilon_{\max}, \qquad (5)$$

where $\varepsilon_{\max}$ is the allowable deviation of DO from the desired trajectory.

The generalized structure diagram that implements this new control strategy is presented in Fig. 5, where $X^{**}(t) \in R^3$ is the vector of the current coordinates of desired position of target point which enter the inputs of each control channel (typical tracking systems). This diagram differs significantly from other diagrams presented in Fig. 1—3.

4. The forming of program signals of dynamical object movement

The truth equation

$$\|\varepsilon_n(t)\| = \\ = \left\| F_n(X_B(t), g_y(\cdot), g_z(\cdot), F_\varepsilon(X^{**}(t), F_u(\cdot), P)) \right\| = 0 \qquad (6)$$

ensures that the DO movement is along the arbitrary spatial trajectory with any achievable velocity and zero deviation from this trajectory. However, solving (6) at a relatively desired position of target point $X^{**}(t) \in R^3$ is possible only for simplest cases, and numerical solutions in real time is very complicated. For this reason, instead of the exact solution presented in (6), numerical solutions should find and use the approximate solution that satisfies (5).

The value $X^{**}(t)$ that provides approximately the truth of (6) we find in the following form:

$$X^{**}(t) = X^*(t) + \Delta X^*(t), \qquad (7)$$

where $\Delta X^*(t) \in R^3$ is the vector of additional program signal that shifts the target point $X^*(t)$ from the desired trajectory of DO movement.

The signal $X^*(t)$ should be entered on inputs of CS DO and the real position $X(t)$ of DO (dashed line in Fig. 6) on distance $\|\varepsilon_n(t)\|$ from trajectory $X^*(t)$ (solid line in Fig. 6). If signal $X^{**}(t)$ (dotted line in Fig. 6) that is copied from $X(t)$ and is located symmetric about trajectory $X^*(t)$ is used instead of signal $X^*(t)$, then real movement of DO $X_B(t)$ (dash-dotted line in Fig. 6) has a decreased distance from trajectory $X^*(t)$. Herewith the following condition is valid:

$$\varepsilon(t) = X^*(t) - X(t) \approx X^{**}(t) - X_B(t) = \varepsilon^*(t).$$

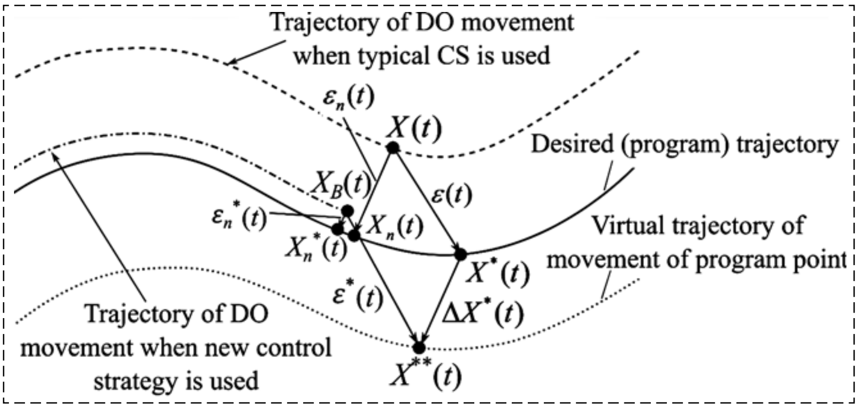

Fig. 6. The schema of DO movement near the program trajectory

It is impossible to define the value $\|\varepsilon_n(t)\|$ a priori, as it depends on the curvature of $X^*(t)$, velocity, DO dynamic parameters and parameters of interaction with the environment. Thus, the $X^{**}(t)$ can be formed during the DO movement only.

The vector $\Delta X^*(t)$can be defined as follows:

$$\Delta X^*(t) = X_n(t) - X(t) = \varepsilon_n(t). \quad (8)$$

Then considering the expressions of (7) and (8), we have

$$X^{**}(t) = X^*(t) + \varepsilon_n(t) = X^*(t) + \Delta X^*(t). \quad (9)$$

The value $\varepsilon^*(t)$ is large when the vector $\Delta X^*(t)$ is entered, but value $\|\varepsilon_n^*(t)\|$ (see Fig. 2) is decreased significantly. However, forming vector $X^{**}(t)$ is a complicated task as DO is on a point $X_B(t)$ near the trajectory $X^*(t)$ and the $X(t)$ cannot be defined. Thus, the vector $\Delta X^*(t)$ that holds DO near to $X^*(t)$ while signaling $X^{**}(t)$ needs to be estimated. We then solve this task by means of CS, whose block diagram is shown in Fig. 7, where BFD is the block of forming the deviation DO from trajectory $X^*(t)$.

The CS shown in this figure has two inputs. The signal $X^*(t)$ enters in the first input, and signal $\Delta X^{**}(t) \approx \Delta X^*(t)$ enters in second input. The signal $\Delta X^{**}(t)$ is calculated during DO movement near the trajectory $X^*(t)$ by means of the expression

$$\Delta X^{**}(t) = k_{n\varepsilon}[X_n^*(t) - X_B(t)] = \\ = k_{n\varepsilon}\varepsilon_n^*, \ (\varepsilon_n^* \ll \varepsilon_n), \quad (10)$$

where $k_{n\varepsilon} = \text{const} > 1$ is the coefficient that is selected so that the condition (5) will be true for all parts of trajectory and the stability of TCS is maintained.

The proposed control strategy of DO movement along trajectory $X^*(t)$ is correct for any stable TCS (1). The main task for forming signal (10) is calculating vector ε_n^*. This task is solved in section 5.

5. Calculation of vector ε_n^*

To calculate the coordinates of point $X_n^*(t)$ and vector ε_n^*, we can use the method proposed in the work [11]. This method requires the numerical solution of system of nonlinear equation by means of a powerful onboard computer. However, we can estimate the $\hat{\varepsilon}_n(t)$ of vector ε_n^*, because the value $\|\varepsilon_n^*(t)\|$ is usually much less than the radius of curvature for all parts of trajectory $X^*(t)$. In this case, the vector $\hat{\varepsilon}_n(t)$ is found as perpendicular to tangent line N of trajectory $X^*(t)$ (see Fig. 8). The coordinates of point $\widehat{X}_n(t)$ (see Fig. 8) are defined in semi-body fixed coordinate frames with axis $\hat{x}$, $\hat{y}$, $\hat{z}$ that are parallel to the axis of GCF, while its center is the center of mass of DO (point $X_B(t)$).

In this coordinate frame, the point $X^*(t)$ is defined by coordinates of vector $\varepsilon(t) = (\varepsilon_{\hat{x}}, \varepsilon_{\hat{y}}, \varepsilon_{\hat{z}})^T$, and point $\widehat{X}_n(t)$ by coordinates of vector $\hat{\varepsilon}_n(t)$. The equation of the tangent line N passing through point $X^*(t)$ and coinciding with vector v* has the following form [12]:

$$\frac{x - \varepsilon_{\hat{x}}}{f_1} = \frac{y - \varepsilon_{\hat{y}}}{f_2} = \frac{z - \varepsilon_{\hat{z}}}{f_3}, \quad (11)$$

where f_1, f_2, f_3 are the elements of vector $f_v(x^*)$ (2). The equation of plane G passing through point $X_B(t)$ and being perpendicular to line N has the following form [12]

$$f_1\hat{x} + f_2\hat{y} + f_3\hat{z} = 0. \quad (12)$$

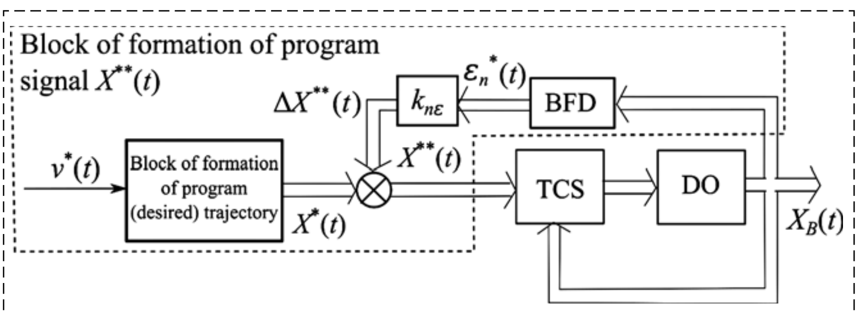

Fig. 7. The block diagram of the system that implements the new control strategy

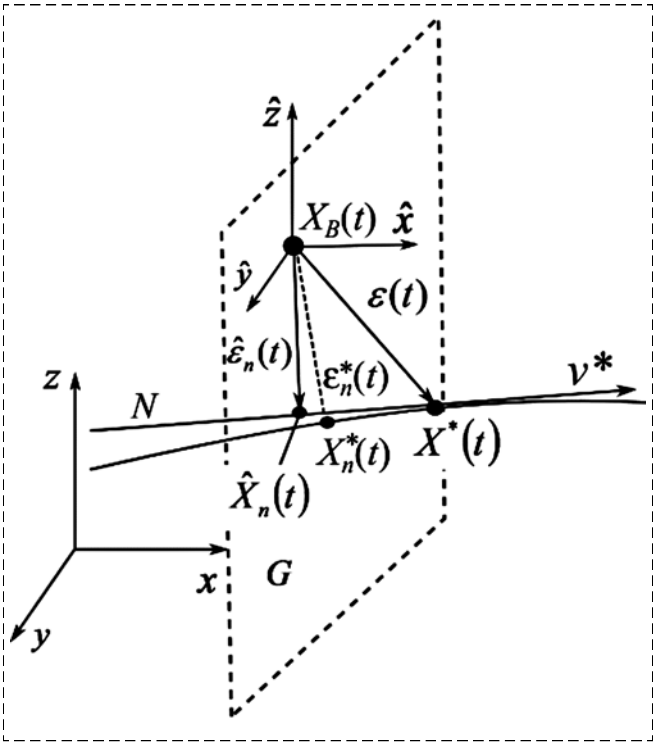

Fig. 8. The schema for calculating vector $\hat{\varepsilon}_n$

After solving system (11) and (12) we have the following expression:

$$\hat{\varepsilon}_n(t) = \begin{bmatrix} f_2^2 + f_3^2 & -f_1 f_2 & -f_1 f_3 \\ \dfrac{f_2^3 + f_2 f_3^2 - f_1}{f_1} & 1 - f_2^2 & -f_2 f_3 \\ \dfrac{f_3^3 + f_2^2 f_3 - f_1}{f_1} & -f_2 f_3 & 1 - f_3^2 \end{bmatrix} \varepsilon(t),$$

which can define the vector $\Delta X^{**}(t)$ with enough accuracy in the form:

$$\Delta X^{**}(t) \approx k_{\varepsilon n} \hat{\varepsilon}_n(t). \qquad (13)$$

6. The results of study of proposed control system

The simulation was performed to study the workability and efficacy of the proposed control strategy. In this simulation, the underwater vehicle (UV) was used as DO. This UV is described by means of the mathematical model from [7]. The actuators of UV have equal parameters and its dynamic, which is described as the aperiodical dynamic link of the first order. The other parameters of this model were the UV mass m_a = 100 kg; the main inertia moments, J_{xx} = 2 kg·m^2, J_{yy} = 10 kg·m^2, and J_{zz} = 10 kg·m^2; the hydrodynamic coefficients, d_{1x} = 25 kg·s^{-1}, d_{2x} = 50 kg·m^{-1}, d_{1y} = 50 kg·s^{-1}, d_{2y} = 100 kg·m^{-1}, d_{1z} = 50 kg·s^{-1}, d_{2z} = 100 kg·m^{-1}, d'_{1x} = 4 Nms, d'_{1y} = 7,5 Nms, d'_{1z} = 7,5 Nms, d'_{2x} = 8 Nms^2, d'_{2y} = 15 Nms^2, and d'_{2z} = 15 Nms^2; the added mass and inertia moments of fluid, λ_1 = 20 kg, λ_2 = 40 kg, λ_3 = 40 kg, λ_4 = 0,5 kg·m^2, λ_5 = 1 kg·m^2, and λ_6 = 1 kg·m^2; the metacentric height, Y_c = 0,02 m; and the time constant of actuators, T_a = 0,1 s.

It is supposed that UV (see Fig. 7) has CS that includes the position and orientation of the simplest controllers in each channel. The transfer function of these controllers has the following perspective, $W(s) = K(T_1 s + 1)/(T_2 s + 1)$, and its parameters have the following values, K = 20, T_1 = 2,51 s, and T_2 = 0,01 s. The parameters of the system of controlling the program signal (see Fig. 7) have the following values, $k_{n\varepsilon}$ = 8.

The planar horizontal movement of UV along trajectory with the described expression $y^*(t) = 10\sin(\pi x^*(t)/20)$ was studied. This movement begins at the zero-initial conditions $x_0^* = 0$ and $y_0^* = 0$, the longitudinal axis of UV is directed always to moving point $X^*(t)$, and the desirable velocity is constant. The desirable yaw angle is calculated by the expression $\varphi^*(t) = \mathrm{arctg}((y^{**}(t) - y(t))/(|x^{**}(t) - x(t)|))$ [7].

The processes of changing the values $v(t)$, $\|\varepsilon^*(t)\|$, $\|\varepsilon_n^*(t)\|$ and $y(t)$ during UV movement with using program signal (9), (10) and v^* = const = 1 m/s are shown in Fig. 9. This figure shows that the maximal value $\|\varepsilon_n^*(t)\|$ is 0,13 m.

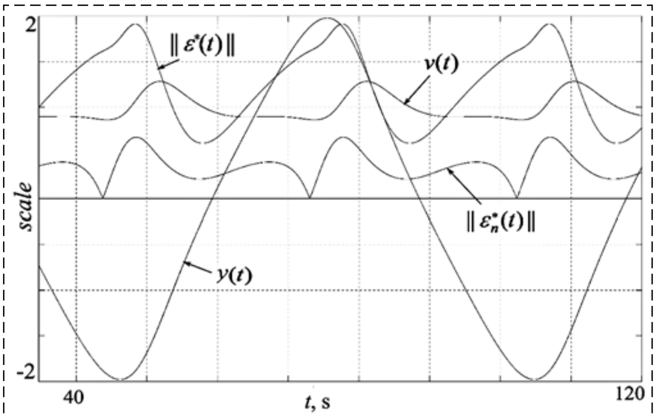

Fig. 9. Process of UV movement when the proposed control strategy is used

$v(t) = scale\,(m/s)$; $y(t) = scale \cdot 5\,(m)$; $\|\varepsilon_n^*(t)\| = scale \cdot 0{,}2\,(m)$; $\|\varepsilon^*(t)\| = 2 \cdot scale\,(m)$

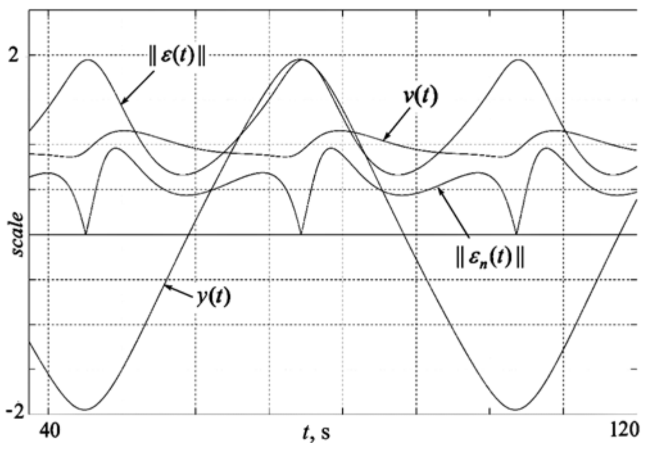

Fig. 10. Process of UV movement when the traditional control strategy is used

$v(t) = scale\,(m/s)$; $z(t) = scale \cdot 5\,(m)$; $\|\varepsilon_n(t)\| = scale(m)$; $\|\varepsilon(t)\| = 2 \cdot scale(m)$

For comparison, the processes of changing these values at signal $X^*(t)$ by means of (2) are shown in Fig. 10. This figure shows that the maximal value of deviation UV from the desired trajectory is 0,95 m. Thus, by using signal $X^{**}(t)$ (9), (10) more, the accuracy of UV movement along desired trajectory was increased 7-fold without changing its CS. Additionally, the values of the dynamical errors $\|\varepsilon(t)\|$ and $\|\varepsilon^*(t)\|$ (see Fig. 6) for program signals $X^*(t)$ and $X^{**}(t)$ are almost equal.

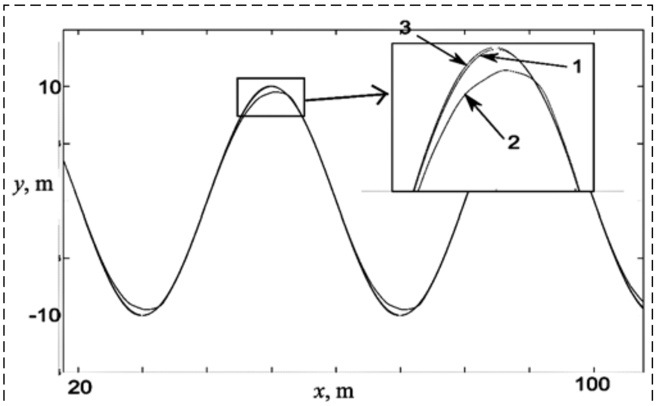

Fig. 11. The features of forming the virtual trajectory

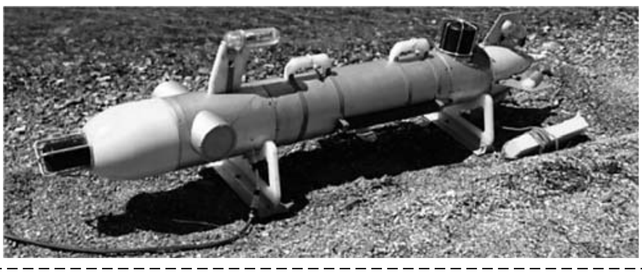

Fig. 12. The external view of AUV MARK

The desired trajectory of UV movement (curve 1), the virtual trajectory forming by means of signal $X^{**}(t)$ (curve 2), and the real trajectory of UV movement (curve 3) are shown in Fig. 11. This figure shows that the UV position and target point $X^{**}(t)$ are always on opposite sides regarding the desired trajectory.

In addition, the marine experiments that use AUV MARK (see Fig. 12) and were designed in Far Eastern Federal University and Institute of Marine Technology Problems were performed [13, 14].

The AUV movement along trajectory is defined by means of Bezier splines passing through points (0,0,0)—(0,20,0)—(20,20,0)—(20,0,0)—(0,0.0) is studied during these experiments. MARK has three control channels: channel controlling forward movement and channels controlling angles of yaw and pitch. The PD-controllers are used in the first and second channels, and the PID-controller is used in third channel. The $k_{n\varepsilon} = 2$ (see Fig. 7) and the AUV desired velocity is 1 m/s.

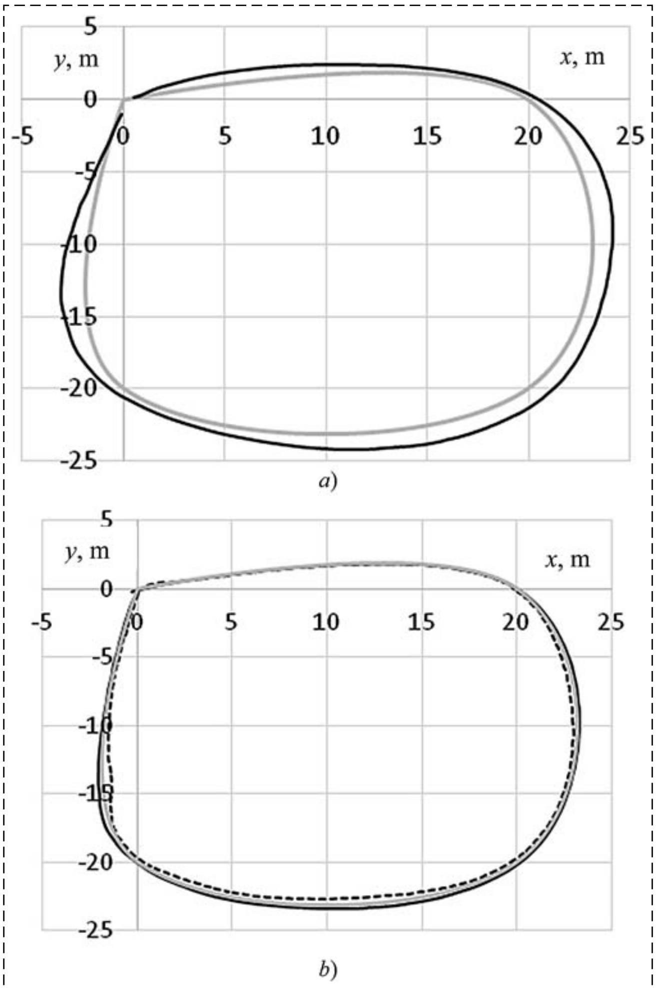

Fig. 13. Trajectories of AUV movement without using (a) the additional loop of forming signal $\Delta X^{**}(t)$ and with the additional loop (b)

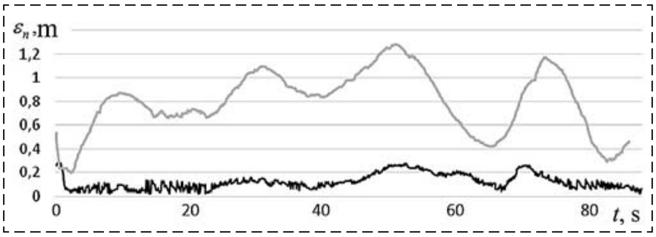

Fig. 14. Change in AUV deviation from the defined trajectory without using an additional loop of forming the signal $\Delta X^{**}(t)$ and the additional loop

The AUV movement (black curve) along the defined trajectory (gray line) without additional loop of forming of signal $\Delta X^{**}(t)$ are shown in Fig. 13a and with using of this loop in Fig. 13b. Here, the dashed curve is the virtual trajectory formed by signal $\Delta X^{**}(t)$.

The deviations of AUV from the defined trajectory using (gray curve) the additional loop of formation of signal $\Delta X^{**}(t)$ and without it (black curve) are shown in Fig. 14. This figure shows that using this additional loop decreases the deviation of AUV from the defined trajectory more than four times (from 1,3 m to 0,3 m).

Thus, the results of mathematical simulation confirm the workability and high efficacy of the new control strategy for DO, which enables designing the systems to automatically form program signals $X^{**}(t)$ for the movement of DO along spatial trajectories.

Conclusions

The new control strategy of high accuracy control of spatial movement of complicated multichannel DO in tracking mode is proposed in this paper. This strategy bases on control of not only DO but also of its program signals and shows that it is easier, useful, and effective. Herewith as against traditional strategies, using virtual trajectories that provide high accuracy movement of DO along desired trajectory is allowed by means of simple controllers even if dynamic errors reach large values. In other words, high accuracy movement of DO along smooth desired trajectories is provided by means of forming new program signals but not by using the complicated high quality CS, which minimized the dynamical errors of tracking.

The results of the mathematical simulation show that using the new control strategy increases the dynamic accuracy of movement of complicated DO along desired trajectories without improving the quality of its tracking CS.

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