Development of Fault-Tolerant Control System for Actuators of Underwater Manipulators

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***Abstract*— This paper presents a one approach for creation of fault-tolerant control systems for electric servo actuators of underwater manipulators, which are describing by nonlinear differential equations with variable and unknown parameters. It is assumed, that the following faults are possible: fault due to action on the output shaft of an unknown external torque and fault, caused by error in actuator position sensor. A bank of diagnostic observers is used to provide the fault isolation and fault estimation processes. So-called logic-dynamic approach is suggested to solve this problem. The advantage of this approach is that it allows considering the systems with non-smooth nonlinearities by linear methods. The fault tolerant control is ensured due to the generation of additional control signals based on estimated value of faults. This provides the reliability of underwater working of manipulators at case of faults. The efficiency of the proposed system is confirmed by mathematical modelling.**

***Index Terms*—underwater manipulators, fault-tolerant control, actuators, fault isolation, fault estimation**

I. Introduction

Today different underwater vehicles with multilink manipulators are the most effective research instrument of the World Ocean [1] and means of fulfillment of various underwater and technical operations in hydrogeology, hydrobiology, geophysics, hydrochemistry, in oil and gaze extraction. Herewith, such manipulators can carry out in supervisory mode following operations [2]: selective sampling of soil probes and geological rocks; collecting bio-organisms; set-up and servicing of different tools; definition of composition and density of the soil using special probes and drills; taking precipitation samples by means of hermetically sealed soil tubes; measurements with thermistor sensors in different layers of sedimentary soil etc.

An important task at the performance of underwater manipulators (UMs) is to increase reliability and safety of these complex technical objects. The arising faults in actuators of UMs can lead to significant reduction of accuracy and therefore quality of work. This task can be solved with the help of fault diagnosis (FD) and fault-tolerant control (FTC) systems [3, 4]. Herewith, the FTC is based on forming additional control signals for automatic stabilization of main parameters of the actuators when faults occur. For forming these additional signals, all arising faults should be timely detected and their values should be estimated by FD system.

The actuators of UMs are described by essentially nonlinear equations with variable parameters [5]. Therefore, it is necessary to use nonlinear methods of FD and FTC. However, most of papers dealing with this problem consider nonlinear systems with differential nonlinearities [6, 7]. Therefore, these methods cannot be effectively used for diagnosis of actuators of the UMs. Today, there are several approaches for diagnosis of systems with no differentiable nonlinearities. Among them there are methods using the algebra of functions [8], the logic-dynamic approach (LDA) [9], and others [10-15]. Whereas the algebra of functions demands complex analytical calculations using symbolic mathematical packages, the LDA allows using the methods of linear algebra for nonlinear systems and provides relatively simple procedure for synthesis of diagnostic observers. There are several FTC systems based on LDA observers [5]. These systems provide exact faults identification and FTC for only actuators of manipulators with fully measured state vector. This condition requires installation of additional sensors for actuators of UMs, which in turn reduces reliability and is not always possible constructively.

At motion of UMs in water, the generalized torques are acting in all its degrees of freedom. These torques are caused by inertial and gravitational forces and forces determined by interaction of working UMs and viscous environment. Values of forces caused by inertial and gravitational forces and interaction of links of MM can be defined with the help of second Lagrange equation. However, the accurate estimation of forces caused by viscous environment can be very difficult. Therefore, these undefined forces can be considered as disturbances affecting on the system. At this case, the actuators of UMs will be described by nonlinear equations with variable and unknown parameters.

This paper considers a solution to the problem of development of the effective FTC system for faults arising in electric servo actuators of the UMs, described by nonlinear differential equations with unknown parameters and not fully known state vector.

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II. Description of Model of the Actuators of UMS

In the paper we will consider the underwater vehicles with the arbitrary UM fixed in point O (see Fig. 1). In general, this UM can have n degrees of freedom. Each degree of the UMs has an electric servo actuator that includes DC motor, reducing gear and sensors measuring the angular position and electrical current of motor circuit.

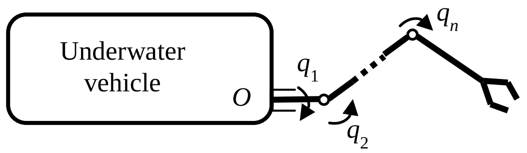


Figure 1. The underwater vehicle with n degrees of freedom UM.

The generalized torque acting on i-th ($i=\overline{1,n}$) actuator of UMs can be expressed in the following form:

$$P_i = H_{ii}(q)\ddot{q}_i + h_i(q,\dot{q})\dot{q}_i + M_{Ei}(q,\dot{q},\ddot{q}) + \tilde{M}_i, \quad (1)$$

where q_i are the corresponding generalized coordinates of the UMs, which are the components of the vector $q \in R^n$; $\dot{q}_i$, $\ddot{q}_i \in R^n$ are the vectors of velocities and accelerations of generalized coordinates; $H_{ii}(q)$ is the diagonal element of the matrix of inertia of the UMs; $h_i(q,\dot{q})$ is the component of Coriolis and velocity forces; $M_{Ei}(q,\dot{q},\ddot{q})$ is the torque action taking into account the gravitational forces and interaction effects between the degrees of freedom of the UMs; $\tilde{M}_i$ is the unknown torque, describing influence of viscous environment on i-th degrees of freedom of the UMs. Further for simplicity we will not write the index i.

Values H , h and M_E with the help of second Lagrange equation are defined. It is assumed that the following typical faults are possible: 1) the fault d1 caused by errors in angular position sensor output $\tilde{\alpha}_r$; 2) the plant fault d2 caused by acting of unknown torque $\tilde{M}$. Considering these faults and (1), model of each actuator of the UMs can be presented by following differential equations [5]:

$$\begin{aligned} \dot{x}_1 &= \frac{1}{i_r}x_2 + d_1, \\ \dot{x}_2 &= -\frac{h^* + k_v}{J+H^*}x_2 + \frac{k_m}{J+H^*}x_3 - \frac{M_{cf} + M_E^*}{J+H^*} + d_2, \\ \dot{x}_3 &= -\frac{k_\omega}{L}x_2 - \frac{R}{L}x_3 + \frac{k_u}{L}u, \end{aligned} \quad (2)$$

where $x_1 = \alpha_r = q$ is the angle of output shaft of reducing gear; $x_2 = \dot{\alpha}$ is the speed of DC motor shaft; R, L and $x_3 = I$, are the resistance, inductance and current of electric motor rotor circuits, accordingly; k_ω is the coefficient of counter-EMF; km is the coefficient of motor torque; k_v is the coefficient of viscous friction; J is the rotational inertia of rotating parts of reduction drive and DC motor; i_r is the coefficient of the reducing gear; u is the control signal; ku is the amplifier gain; $M_{cf} = M_{cf0}sign(\dot{\alpha})$ is moment of Coulomb friction; M_{cf0} is coefficient of Coulomb friction; H^*, h^*, M_E^*, are respective values determined by the equations $H^* = \frac{H}{i_r^2}$, $h^* = \frac{h}{i_r^2}$, $M_E^* = \frac{M_E}{i_r}$.

The variables d1 and d2 in (2) represent the effects of faults on the system and can be presented in next form:

$$d_1(t) = \dot{\tilde{\alpha}}_r, \; d_2(t) = -\tilde{M}^*/(J+H^*), \quad (3)$$

where $\tilde{M}^* = \tilde{M}/i_r$.

The system (2) can be represented by the differential equation in a matrix form as follows:

$$\dot{x}(t) = Fx(t) + Gu(t) + B(x) + Dd, \quad (4)$$
$$y(t) = Nx(t),$$

where

$$F = \begin{bmatrix} 0 & 1/i_r & 0 \\ 0 & -(k_v + h^*)/(J+H^*) & k_m/(J+H^*) \\ 0 & -k_\omega/L & -R/L \end{bmatrix}, \; x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix},$$

$$D = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, G = \begin{bmatrix} 0 \\ 0 \\ k_u/L \end{bmatrix}, \; y = \begin{bmatrix} \alpha_r \\ I \end{bmatrix}, \; d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix},$$

$$N = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \; B(x) = \begin{bmatrix} 0 \\ -(M_{cf} + M_E^*)/(J+H^*) \\ 0 \end{bmatrix}.$$

The arising faults d_1 and d_2 considerably reduce the working capacity and performance of UMs. These faults should be promptly detected and estimated. Then the FTC can be used. The traditional methods of diagnosis that focuses on systems described by linear models cannot provide the solution to the problem of synthesis of FD and FTC systems for electric servo actuators of the UMs described by model (4).

In this paper, another synthesis method of FTC systems is proposed. This method includes three main stages: 1) the synthesis of bank of observers based on of LDA [9], which allows to solve the problem of FD of actuators of UMs with non-differentiable non-linearity by linear methods; 2) estimation of values of faults; 3) the formation of control signals due to the use of additional signals of residuals which guarantee quick parrying of occurring faults and provides accurate stabilization of the dynamic properties of actuators.

III. Synthesis of FTC System

The LDA includes following steps [9]. 1. Replacing the initial nonlinear system (4) by linear system. 2. Solving the FD for the linear system with some additional restrictions and obtaining the bank of linear observers. 3. Transforming the linear observers into the nonlinear ones. The feedback signals by residual are introduced in observers for fault estimation [5]. The nonlinear diagnostic observers with residual feedbacks detecting the faults have following general form

$$\begin{aligned} \dot{x}_* &= F_* x_* + G_* u + B_*(x_*) + Vy + z(r), \\ y_* &= N_* x_*, \end{aligned} \tag{5}$$

where $x_* \in R^k$ is the state vector of the observer; y_* is the output signal; $F_* \in R^{k\times k}$; $G_* \in R^{1\times k}$; $B_* \in R^k$; $V \in R^{k\times 2}$ and $N_* \in R^{1\times k}$ are matrices describing the observer; k is dimension of the observer; $z(r) \in R^k$ is feedback vector. It is known [9] that the matrices F_* and N_* can be represented in next form:

$$F_* = \begin{bmatrix} 0 & 1 & 0 & \dots 0 \\ 0 & 0 & 1 & \dots 0 \\ . & . & . & . \\ 0 & 0 & 0 & \dots 0 \end{bmatrix}, \; N_* = [1 \quad 0 \quad 0 \quad \dots \quad 0].$$

The observer (5) generates the residual $r(t) = Cy(t) - y_*$ for certain row matrix $C \in R^2$ which should be determined. If there are no faults and $d = 0$, then $r(t) = 0$, if a fault occurs, $r(t) \neq 0$. It is well-known [9] that for the observer design, the matrix Φ out plays the main role. In absent of faults condition $\Phi x = x_*$ is satisfied. In the absence of faults, the following well-known set of equations holds [9]:

$$\begin{aligned} &N_* \Phi = CN, \; \Phi F = F_* \Phi + VN, \\ &G_* = \Phi G, B_* = \Phi B. \end{aligned} \tag{6}$$

The first order observer O_1 for estimation of the value of fault d_1 can be described by matrices:

$$F_* = 0, \; N_* = 1, \Phi = [1 \quad 0 \quad L/k_\omega i_r],$$
$$G_* = k_u / k_\omega i_r, \; V = [0 \quad -R/k_\omega i_r], \; C = [1 \quad L/k_\omega i_r],$$
$$B_* = 0, \; z(r) = z_1 r,$$

where $z_1 > 0$ is constant coefficient of residual feedback.

Since the expression $\Phi D_1 = 1$, where D_1 is the first column of matrix D, is not zero, and the expression $\Phi D_2 = 0$, where D_2 is the second column of matrix D, the obtained observer will be sensitive only to the fault d_1.

The value of fault d_1 and value of error in angular position sensor output $\tilde{\alpha}_r$ can be determined as follows [5]:

$$d_1(t) = z_1 r(t), \; \tilde{\alpha}_r = \int d_1 dt.$$

The second order observer O_2 for estimation of the value of fault d_2 can be described by matrices:

$$F_* = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \; N_* = [1 \quad 0],$$

$$B_* = \begin{bmatrix} 0 \\ \dfrac{k_\omega M_E}{L(J+H^*)} + \dfrac{k_\omega M_{cf0}}{L(J+H^*)} sign(\dfrac{L(\frac{k_v + h^*}{J+H^*} I - x_{*2})}{k_\omega}) \end{bmatrix};$$

$$\Phi = \begin{bmatrix} 0 & 0 & 1 \\ 0 & -\dfrac{k_\omega}{L} & \dfrac{k_v + h}{J+H^*} \end{bmatrix}, \; C = [0 \quad 1],$$

$$G_* = \begin{bmatrix} \dfrac{k_u}{L} \\ \dfrac{(k_v + h^*)k_u}{L(J+H^*)} \end{bmatrix}, \; V = \begin{bmatrix} 0 & -\dfrac{L(k_v + h^*) + R(J+H^*)}{L(J+H^*)} \\ 0 & -\dfrac{k_m k_\omega + (k_v + h^*)R}{L(J+H^*)} \end{bmatrix}.$$

where x_{*2} is second state variable of observer O_2.

The expression $\Phi D_1 = [0 \quad 0]^T$ and expression $\Phi D_2 = [0 \quad -k_\omega / L]$. Therefore it is possible to see, that obtained observer will be sensitive only to the fault d_2.

To estimate of the fault d_2, it is proposed to introduce a feedback signal that will ensure the operation of the observer in sliding mode [14, 16]. This residual signal feedback should eliminate of mismatch between diagnosed object and observer, i.e. $e = \Phi x - x_* = 0$, even in the presence of fault d_2.

According to [14], feedback signal $z(r)$ can be chosen as follows:

$$z(r) = [0 \quad -z_2 sign(S) - f(t)]^{\mathrm{T}}, \tag{7}$$

where $S = r(t) + c\dot{r}(t)$; c is a positive coefficient, $f(t) = \dot{\Phi} x = \dfrac{\dot{h}^*(J+H^*) - h(k_v + h^*)}{(J+H^*)^2} I$. For the existence of a sliding mode, the following condition must be fulfilled:

$$S\dot{S} = S(\dot{r}(t) + c\ddot{r}(t)) = S(\dot{r}(t) + c(-k_\omega d_2 / L - z_2 sign(S)) < 0.$$

Thus, to satisfy this condition, it is necessary:

$$z_2 \geq \left| \frac{\dot{r}_{\max} + c(-k_\omega d_{2\max} / L)}{c} \right|,$$

where $\dot{r}_{\max}$ and $d_{2\max}$ are absolute values of the maximum possible values of $\dot{r}$ and d_2.

After the introduction of the feedback signal (7), the dynamics of the observer O_2 will be described by the equation $S = 0$.

When feedback of this type is used, residual r(t) will reach zero in a finite time interval and the feedback signal completely compensates the effect of the fault on the system, and faults value can be determined as follows:

$$\tilde{M}^* = -z_{eq}(J + H^*), \quad (8)$$

where z_{eq} is value equivalent to the feedback signals, which are the average value of the signal $z(r)$ [16].

The next step of synthesis of the FTC system is forming a control law for the compensation of the estimated faults. Actuators of the UMs are described by nonlinear differential equations with variable parameters. The control law for such objects can be formed using an approach of synthesis of corrective devices, which provides stabilization of the parameters of the control object to the nominal values [17].

In the beginning of this approach for actuators of UMs, the required dynamic properties are defined. These properties for DC motors are determined by the differential equation with constant coefficients, such as: $LJ\dddot{\alpha} + RJ\ddot{\alpha} + k_\omega k_m \dot{\alpha} = k_u k_m \tilde{u}$, where $\tilde{u}$ is a control signal of input of FTC system.

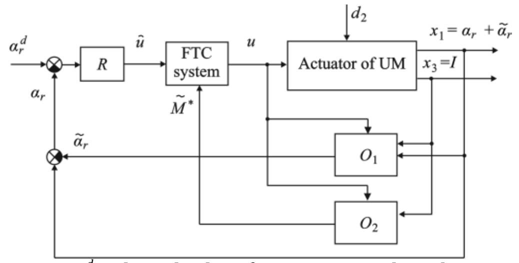
The expression for the highest derivative of the output variable $\dddot{\alpha}$ is determined from this equation. Substitution of it into the original system of differential equation (2) with variable coefficients allows to obtain required control law as a function of lower derivatives of the output variable. This provides the specified dynamic properties and the quality of the control object. It is possible to stabilize the characteristics of each actuator at nominal level, by introducing the additional residual (8) formed by using observer O_2 in control law. Finally fault-tolerant control law by each actuator of UMs takes the form:

$$u = \frac{(J + H^*)}{J_n}\tilde{u} + \frac{L\ (2h^* + k_v)}{k_u k_m}\ddot{\alpha} + \frac{1}{k_u k_m}[L\dot{h}^* + R(h^* + k_v) + k_\omega k_m(1 - \frac{(J + H^*)}{J_n})]\dot{\alpha} + \frac{R}{K_у K_м}[M_E^* + M_{cf} + \tilde{M}^*] + \frac{L}{k_u k_m}[\dot{M}_E^* + \dot{\tilde{M}}^*]. \quad (9)$$

where J_n is nominal value of rotational inertia of rotating parts of reduction drive and DC motor.

To compensate the fault d_1 it is necessary to subtract value $\tilde{\alpha}_r$ from the signal output from the output position sensor of the actuators, as shown in the system in Fig. 2.

The analysis of components of law (9) shows that the synthesis of proposed fault-tolerant control system for each actuators of UMs is no represented the difficult. This system can be realized by using the typical microcontrollers.



α_r^d is desired value of α_r, *R* is a typical regulator

Figure 2. Generalized block diagram of the electric servo actuator of UMs with FTC system.

IV. Study of Effectiveness of FTC System

Analysis of effectiveness of developed FTC system was implemented using model of UM with three degrees of freedom. The FTC system was synthesized for electric servo actuator of second degree of freedom of this UM. The results for other degree of freedom of the UM are similar.

Parameters of UM have the following values: $l_1 = l_2$ = 0.5 m are lengths of UM links; $m_1 = m_2 =$ 3.9 kg are masses of links. The links centers of size coincide with their centers of weights. Links have neutral buoyancy and cylindrical form with base radius 0.05 m. The electric drive servo actuator is described by following set of parameters: R = 0.5 Ω, L = 0.0005 H, k_ω = 0.04 V s, k_m = 0.04 Nm/A, J = 10-3 kg·m^2, i_r = 100, $k_v = 0.005$ N m s/rad, $M_{cf0} = 0.02$ Nm, k_u = 800.

Effects of the interference in the model (2) for the second degree of freedom of UM are described by the following equations:

$$H = 1.86 + 0.5\cos q_3,\ h = -0.5\dot{q}_3 \sin q_3,$$
$$M_E = [0.17 + 0.25\cos q_3]\ddot{q}_3 - 0.25\dot{q}_3^2 \sin q_3 + 21.3\sin q_2 + 4.9\sin(q_2 + q_3) - [0.7\sin 2q_2 + 0.086\sin 2(q_2 + q_3) + 0.25\sin(2q_2 + q_3)]\dot{q}_1^2.$$

The input signal $q_1 = \sin(0.5t)$, $q_2 = \alpha_r^d = \sin(1.5t)$, $q_3 = \sin(0.7t + 0.1)$ was applied to the electric servo actuator.

Faults were presented by changing the following values:

– adding the torque $\tilde{M}^* = 0.04\sin 0.8\,t$ Nm.

– adding error of angular position sensor $\tilde{\alpha}_r = 0.002\,rad$ at the time t_1 = 5 s.

Values of estimated value of faults are shown on the Fig. 3 and Fig. 4. It follows from these figures that the constructed system provides accurate estimation of occurred faults. Fig. 5 shows the value of dynamic error of position of actuator with FTC system (curve 1) and without FTC system (curve 2).

The results of simulation confirm the efficiency of the proposed FTC system (9) for actuators of UMs.

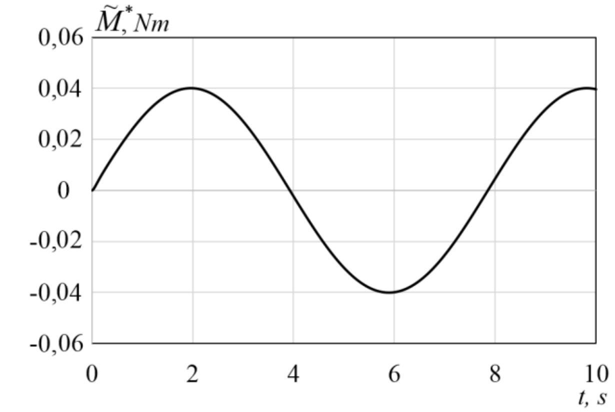


Figure 3. Estimation of $\tilde{M}^*$ value by proposed FD system.

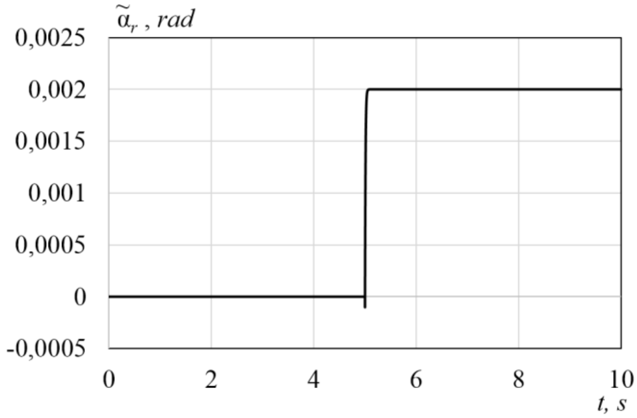


Figure 4. Estimation of fault $\tilde{\alpha}$ value by proposed FD system.

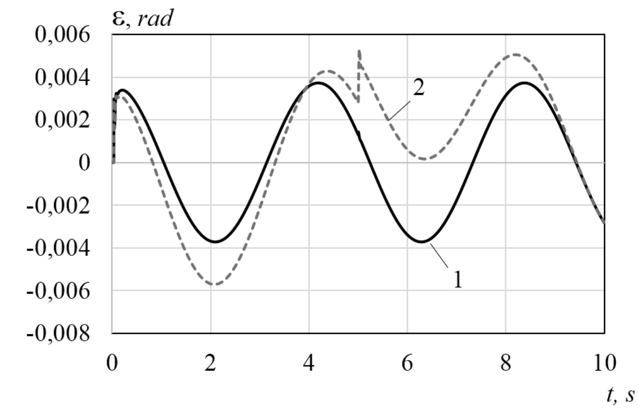


Figure 5. Dynamic error of position of actuator with FTC system and without FTC system.

V. Conclusion

An effective FTC system for electric servo actuators of UMs is suggested. Two typical faults in actuators of UMs were considered. For detection and estimation of these faults bank of observers with residual signal feedbacks were synthesized. It was proposed to realize the FTC by generation of additional control signals based on identified value of faults. As a result, it is possible provide the reliability of underwater working of manipulators in the event of faults.

Acknowledgment

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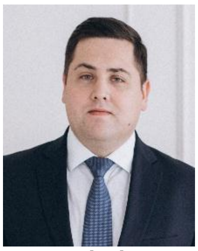

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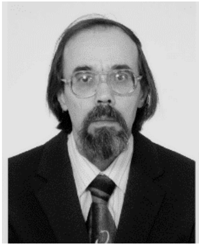

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