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The New Approach for Synthesis of Diagnostic System for Navigation Sensors of Underwater Vehicles

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Abstract

In this paper, new approach for synthesis of the diagnostic system for navigation sensors of underwater vehicles (UVs) is developed and investigated. Proposed system is synthesized by using kinematic model of UVs and data fusion of sensors signals. The advantage of this approach is that it allows detecting and isolating faults in sensors of UVs at performance of underwater missions in unknown environment with unknown external disturbances.
The results of performed simulation have completely confirmed the working capacity and high quality of the proposed approach.

Keywords: diagnostic system; underwater vehicles; sensors; faults

1. Introduction

Today the development of different types of UVs for fulfillment of underwater operations received increasing attention. The main fields of UVs use are the monitoring and maintenance of offshore structures or pipelines, the exploration of the sea bottom, fulfillment of underwater engineering operations and so on. Often UVs should autonomously operate during long periods of time in unstructured environments with unknown external disturbances in which the undetected faults usually implies loss of the vehicle. Navigation sensors are one of the most important components of the UVs, which are necessary to motion control and navigation at performance of autonomous underwater missions.

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Obviously, the failure of navigation sensors arising at the autonomous mission fulfillment will lead to erroneous mission fulfillment or loss of vehicle. Therefore, it is necessary to detect, isolate and estimate faulty sensor as soon as possible. In case of faults arising, the diagnostic system should send information about detected faults to control system UVs which should decide to stop the mission or to continue with by using special correction of control signals (case of fault tolerant control).

There are several different synthesis methods of diagnostic system for UVs [2-11]. These strategies use analytical model based techniques including Kalman filters, diagnostic (Luenberger like) observers, parity relations, neural network and so on. Analytical model based methods allow obtaining better performances of diagnostic procedure but need to use the sufficiently perfect mathematical models of vehicle dynamics. The characteristic feature of such models is that the equations of the vehicle motion are strongly non-linear, coupled and has the variables and unknown parameters.

There are several approaches [2, 3] to robust diagnosing of UVs, based on use of expanded Kalman filters. Their advantage is relative simplicity of the realization, however thus synthesized observers are capable to detect faults effectively only at horizontal movement of the UVs with low speed.

In works [4-6], the sliding observer is proposed to use for formation of value of faults. Doubtless advantage of the given approaches is tolerance of the synthesized observers to unknown but slowly changing parameters of UVs. However, the big problem interfering practical introduction of such systems is the problem of «chattering».

There are synthesis methods for observers with adaptive feedback [7], which allow detecting faults of UVs at the presence of not exactly known parameters of model. However this method has difficulties with application in real time due to large calculations.

Hereby problem of developing of effective diagnostic system for navigation sensors of UVs is important and topical. For solving this problem in paper is proposed new approach for synthesis of diagnostic system for navigation sensors of UVs by using kinematic model of UVs and data fusion of sensors signals. In this case, the actual UVs sensors measurements are compared with a fault-free observers output signals driven by the control signals and measurements of AUV sensors. Difference between the actual sensor measurement and corresponding observer output signal is a residual signal that carries all possible information about the faults in the AUV components.

This system provides exact detection and isolation of faults in sensors of UVs at performance of underwater missions in unknown environment with unknown external disturbances.

2. Description of UVs mathematical model

The UVs dynamic behaviour can be described by several sets of nonlinear differential equations. The UVs precise mathematical models are very complex and have the variable and unknown parameters. Therefore, diagnostic system synthesized on basis of this model cannot provide exact faults detection and isolation. Researches have shown, that it is possible to synthesize the diagnostic system for navigation sensors using only kinematic model of UVs.

In general, kinematic model of UVs can be present in matrix form [1]:

$$\dot{x} = J(\eta)\upsilon \tag{1}$$

where $\eta = [x, y, z, \varphi, \theta, \psi]^{\mathrm{T}} \in R^6$ is the vector of position and attitude of UVs in absolute coordinate system; $\upsilon = [\upsilon_x, \upsilon_y, \upsilon_z, \omega_x, \omega_y, \omega_z]^{\mathrm{T}} \in R^6$ is the vector of projections of linear and angular velocities of UVs on the axes of joined coordinate system; T is a symbol of transposition; $J(x)$ is the matrix of transition from jointed to absolute coordinate system which has a view [1]:

$$J(x) = \left[\begin{array}{c:c} J_1(x) & 0 \\ \hdashline 0 & J_2(x) \end{array}\right], \tag{2}$$

where $J_1(x)=\begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\varphi - \\ & -\cos\psi\sin\theta\sin\varphi & \sin\psi\sin\varphi+ \\ & & +\cos\psi\cos\varphi\sin\theta \\ \sin\psi\cos\theta & \cos\psi\cos\varphi+ & -\cos\psi\sin\varphi+ \\ & +\sin\varphi\sin\theta\sin\psi & +\sin\theta\sin\psi\cos\varphi \\ -\sin\theta & \cos\theta\sin\varphi & \cos\theta\cos\varphi \end{bmatrix}$, $J_2(x)=\begin{bmatrix} 1 & \sin\varphi\tan\theta & \cos\varphi\tan\theta \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \frac{\sin\varphi}{\cos\theta} & \frac{\cos\varphi}{\cos\theta} \end{bmatrix}$.

The set of onboard navigation sensors of UVs depends on its type and appointment. The most underwater vehicles, intended for autonomous performance of various missions, have the following set of navigation sensors:

1) the Doppler speed log, measuring linear speeds (v_x, v_y, v_z) of UV in joint coordinate system;
2) the sensors of angular speeds of UV (ω_x, ω_y, ω_z) concerning joint coordinate system;
3) the sensor of orientation of UV (φ, θ, ψ), measuring angles of heel, trim and course in absolute coordinate system;
4) the hydroacoustic navigation system (HNS), measuring linear coordinates of UVs (x, y) in absolute coordinate system;
5) the sensor of depth of UV (z), measuring coordinate of z in absolute coordinate system.

Thus all components of vectors of v and x in kinematic model of UVs (see equation 1) are measured by sensors. At this, the faults dv and dx can be arising in these sensors:

$$\tilde{x}=x+dx,\quad \tilde{v}=v+dv,$$

where $dv=[dv_x, dv_y, dv_z, d\omega_x, d\omega_y, d\omega_z]^T$, $dx=[dx, dy, dz, d\varphi, d\theta, d\psi]^T$; $\tilde{x}$, $\tilde{v}$ are output signals of navigation sensors with faults.

In case faults are absent, all elements of vectors of dv and dx are equal to zero.

There are many different causes leading to the sensors fault. The faulty components should be early detected and isolated by the diagnostic system to avoid the erroneous mission fulfillment or loss of the UVs. In this case, the detection of incipient faults is of particular importance.

At the isolation and estimation of faults values, it is necessary to use mathematical model of UVs. In this paper, we propose to use only kinematic model (expressions (1), (2)) as it connects all parameters of motion of UVs and the variables measured by its navigation sensors. Besides, this model does not contain variables or uncertain coefficients that allows providing high precision of work of diagnostic system.

3. Synthesis of diagnostic system

The residuals generation consists in producing a signal, which carries information about the faults. For each sensor, the particular observer to generate the residual will be used. Diagnosing is carried out by means of check of some algebraic ratios to which have to satisfy output signals of UVs sensors and observers in the absence of faults.

Such observer is driven by the measured components of the state vector of UVs. Vectors of output signals of sensors $\tilde{x}$ and observers $\bar{x}$ are compared therefore the vector of residual r is formed (at the absence of faults $r = 0$).

For diagnosing of sensors, the observers modeling an output signal of this sensor based on output signals of other sensors are used.

Let introduce the observers O_1-O_6, which model the signals x, y, z, φ, θ, ψ accordingly and are described by equations similar to (1)

$$\dot{\bar{x}}=J(\tilde{x})\tilde{v}\,. \tag{3}$$

At this, the residual vector $r=[r_1, r_2, r_3, r_4, r_5, r_6]^T$ is formed as

$$r=\tilde{x}-\bar{x}\,. \tag{4}$$

If we rewrite the (3) by taking into account equation (2) we can obtain the equations for observers:

$$\begin{aligned}
\dot{\tilde{x}}_1 &= J_{11}\tilde{v}_x + J_{12}\tilde{v}_y + J_{13}\tilde{v}_z, \\
\dot{\tilde{x}}_2 &= J_{21}\tilde{v}_x + J_{22}\tilde{v}_y + J_{23}\tilde{v}_z, \\
\dot{\tilde{x}}_3 &= J_{31}\tilde{v}_x + J_{32}\tilde{v}_y + J_{33}\tilde{v}_z, \\
\dot{\tilde{x}}_4 &= J_{44}\tilde{\omega}_x + J_{45}\tilde{\omega}_y + J_{46}\tilde{\omega}_z, \\
\dot{\tilde{x}}_5 &= J_{55}\tilde{\omega}_y + J_{56}\tilde{\omega}_z, \\
\dot{\tilde{x}}_6 &= J_{65}\tilde{\omega}_y + J_{66}\tilde{\omega}_z.
\end{aligned} \tag{5}$$

To isolate the fault in UVs sensors we need to designate the relations between faults in the components and residuals. These relations can be represented in the form of the faults matrix M_f . The rows of this matrix correspond to the residuals and columns correspond to the faults in the components. The values of the faults matrix are 0 and 1 which reflect a fact of sensitivity of residuals to the fault in some component. If residual is sensitive to particular fault, the intersection of corresponding row and column of this matrix is indicated by the value 1; otherwise 0. In our case, the faults matrix M_f will have the following form:

	r_1	r_2	r_3	r_4	r_5	r_6
dv_x	1	1	1	0	0	0
dv_y	1	1	1	0	0	0
dv_z	1	1	1	0	0	0
$d\omega_x$	0	0	0	1	0	0
$d\omega_y$	0	0	0	1	1	1
$d\omega_z$	0	0	0	1	1	1
dx	1	0	0	0	0	0
dy	0	1	0	0	0	0
dz	0	0	1	0	0	0
$d\varphi$	1	1	1	1	1	1
$d\psi$	1	1	0	0	1	0
$d\theta$	1	1	1	1	0	1

To isolate faulty sensor we need compare the results of residual evaluation with signatures of particular faults. The signature of the i -th fault is the i -th line of the faults matrix M_f . If they coincidence, this means that the fault did occurs in correspond UVs sensor. As follows from the faults matrix M_f , the faults dv_x, dv_y, dv_z and $d\omega_y$ are not distinguished from one another because its signatures are similar. Therefore, the faulty sensor cannot be isolated correctly by the diagnostic system. To improve the fault isolation property, the additional observers are suggested.

Let's express from first, second, third and fifth equations of (5) the following values:

$$\tilde{v}_1 = \frac{\dot{x}_1 - (J_{12}\tilde{v}_2 + J_{13}\tilde{v}_3)}{J_{11}},$$
$$\tilde{v}_2 = \frac{\dot{x}_2 - (J_{21}\tilde{v}_1 + J_{23}\tilde{v}_3)}{J_{22}},$$
$$\tilde{v}_3 = \frac{\dot{x}_3 - (J_{31}\tilde{v}_1 + J_{32}\tilde{v}_2)}{J_{33}}, \qquad (6)$$
$$\tilde{v}_5 = \frac{\dot{x}_5 - J_{56}\tilde{v}_6}{J_{55}},$$

and substitute $\tilde{v}_1$ into O_3, $\tilde{v}_2$ into O_1, $\tilde{v}_3$ into O_2 and $\tilde{v}_5$ into O_4. As a result, we can obtain the additional observers O_7 - O_{10}, residuals of which did not depend from dv_y, dv_z, dv_x *and* $d\omega_y$ accordingly. After introduction of these observers, matrix M_f will be:

	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	r_9	r_{10}
dv_x	1	1	1	0	0	0	1	1	0	0
dv_y	1	1	1	0	0	0	0	1	1	0
dv_z	1	1	1	0	0	0	1	0	1	0
$d\omega_x$	0	0	0	1	0	0	0	0	0	1
$d\omega_y$	0	0	0	1	1	1	0	0	0	0
$d\omega_z$	0	0	0	1	1	1	0	0	0	1
dx	1	0	0	0	0	0	1	0	1	0
dy	0	1	0	0	0	0	1	1	0	0
dz	0	0	1	0	0	0	0	1	1	0
$d\varphi$	1	1	1	1	1	1	1	1	1	1
$d\psi$	1	1	0	0	1	0	1	1	1	1
$d\theta$	1	1	1	1	0	1	1	1	1	1

Thus, all lines of a matrix of M_f (signature of faults) are various. As a result possible it becomes unambiguous to define the faulty sensor.

Let us introduce the vector *I*, such that:

$$I = \begin{pmatrix} I_1 \\ I_2 \\ \dots \\ I_{10} \end{pmatrix}, \quad I_i = \begin{cases} 1, & |r_i| \geq r_{i0}, \\ 0, & |r_i| \leq r_{i0}, \end{cases}$$

where r_{i0} is a the size defining a threshold of sensitivity of the observer, $i = \overline{1,10}$. Thus, *i*-th element of vector of *I* will be equal 1 if residual r_i exceed threshold value, and to zero otherwise. Next, compare vector *I* and signatures of faults to obtain a vector *L*:

$$L = \begin{pmatrix} L_1 \\ L_2 \\ \ldots \\ L_{12} \end{pmatrix}, \quad L_j = \begin{cases} 1, & I = M_j, \\ 0, & I \neq M_j, \end{cases}$$

where $j = \overline{1,12}$, M_j – *j*-th line of matrix M_f. All the elements of the vector *L* will be zero when no faults occurred. If an *i*-th defect occurred, then *i*-th element of vector *L* becomes equal to 1 and the rest will be zero. Thus, the vector *L* accurately detects the presence and location of faults, and the problem of localization of defects can be considered solved.

4. Results of simulation of diagnostic system

To investigate the performance and effectiveness of the proposed synthesis method of diagnostic system, simulations were performed. In this simulation the following UV mathematical model was used:

$$(M_R + M_A)\dot{\upsilon} + (C_R(\upsilon) + C_A(\upsilon))\upsilon + g(x) + D(\upsilon)(\upsilon) = \tau \,, \tag{7}$$

where $D(\upsilon) = diag(d_{1x}, d_{1y}, d_{1z}, d'_{1x}, d'_{1y}, d'_{1z}) + diag(d_{2x}|\upsilon_x|, d_{2y}|\upsilon_y|, d_{2z}|\upsilon_z|, d'_{2x}|\omega_x|, d'_{2y}|\omega_y|, d'_{2z}|\omega_z|)$; $g(\eta) \in R^6$ is the vector of hydrostatic forces and torques; $\tau = [T_x, T_y, T_z, M_x, M_y, M_z]^T \in R^6$ is the vector of projection of thrusts on the axes of joined coordinate system; d_1, d_2, d'_1, d'_2 are coefficients of viscous friction corresponding linear and square dependences of hydrodynamic forces and torques from UV velocities on its separate degrees of freedom;

$$M_R = \begin{bmatrix} m_r & 0 & 0 & 0 & m_r Y_c & 0 \\ 0 & m_r & 0 & -m_r Y_c & 0 & 0 \\ 0 & 0 & m_r & 0 & 0 & 0 \\ 0 & -m_r Y_c & 0 & J_{xx} & -J_{xy} & -J_{xz} \\ m_r Y_c & 0 & 0 & -J_{xy} & J_{yy} & -J_{yz} \\ 0 & 0 & 0 & -J_{xz} & -J_{yz} & J_{zz} \end{bmatrix}; \; M_A = -\begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} & \lambda_{16} \\ \lambda_{12} & \lambda_{22} & \lambda_{23} & \lambda_{24} & \lambda_{25} & \lambda_{26} \\ \lambda_{13} & \lambda_{23} & \lambda_{33} & \lambda_{34} & \lambda_{35} & \lambda_{36} \\ \lambda_{14} & \lambda_{24} & \lambda_{34} & \lambda_{44} & \lambda_{45} & \lambda_{46} \\ \lambda_{15} & \lambda_{25} & \lambda_{35} & \lambda_{45} & \lambda_{55} & \lambda_{56} \\ \lambda_{16} & \lambda_{26} & \lambda_{36} & \lambda_{46} & \lambda_{56} & \lambda_{66} \end{bmatrix};$$

m_r is the mass of UV, λ_{ij} are elements corresponding added masses and inertia moments of fluid $(i, j = 1,\ldots,6)$, Y_c is the metacentric height of UV, $J_{xx}, J_{yy}, J_{zz}, J_{xy}, J_{xz}, J_{yz}$ are the UV inertia moments relatively its main and auxiliary inertia axes;

$$C_R(\upsilon) = \begin{bmatrix} 0 & C_{11}(\upsilon) \\ C_{21}(\upsilon) & C_{22}(\upsilon) \end{bmatrix}; \; C_A(\upsilon) = \begin{bmatrix} 0 & 0 & 0 & 0 & \alpha_3(\lambda,\upsilon) & -\alpha_2(\lambda,\upsilon) \\ 0 & 0 & 0 & -\alpha_3(\lambda,\upsilon) & 0 & \alpha_1(\lambda,\upsilon) \\ 0 & 0 & 0 & \alpha_2(\lambda,\upsilon) & -\alpha_1(\lambda,\upsilon) & 0 \\ 0 & \alpha_3(\lambda,\upsilon) & -\alpha_2(\lambda,\upsilon) & 0 & \beta_3(\lambda,\upsilon) & -\beta_2(\lambda,\upsilon) \\ -\alpha_3(\lambda,\upsilon) & 0 & \alpha_1(\lambda,\upsilon) & -\beta_3(\lambda,\upsilon) & 0 & \beta_1(\lambda,\upsilon) \\ \alpha_2(\lambda,\upsilon) & -\alpha_1(\lambda,\upsilon) & 0 & \beta_2(\lambda,\upsilon) & -\beta_1(\lambda,\upsilon) & 0 \end{bmatrix}.$$

The model (7) had following values of parameters: $m_r = 300kg$, $Y_c = 0.02m$, $J_{xx} = 9kg \cdot m^2$, $J_{yy} = 30kg \cdot m^2$, $J_{zz} = 30kg \cdot m^2$; $\lambda_{11} = 80kg$, $\lambda_{22} = 140kg$, $\lambda_{33} = 140kg$, $\lambda_{44} = 5kg \cdot m^2$, $\lambda_{55} = 30kg \cdot m^2$, $\lambda_{66} = 30kg \cdot m^2$, $\lambda_{ij} = 0, \quad i \neq j, i, j = \overline{(1,6)}$; $d_{1x} = 30\frac{kg}{s}$, $d_{2x} = 10\frac{kg}{m}$, $d_{1y} = 60\frac{kg}{s}$, $d_{2y} = 30\frac{kg}{m}$, $d_{1z} = 60\frac{kg}{s}$, $d_{2z} = 30\frac{kg}{m}$, $d'_{1x} = 20N \cdot m \cdot s$, $d'_{2x} = 10N \cdot m \cdot s^2$, $d'_{1y} = 40N \cdot m \cdot s$, $d'_{2y} = 20N \cdot m \cdot s^2$, $d'_{1z} = 40N \cdot m \cdot s$, $d'_{2z} = 20N \cdot m \cdot s^2$.

The simulation of work of offered diagnostic system is carried out at moving of UV under acting of thrusts $T_x = 50 \cdot \sin(0.03 \cdot t)$, $T_y = 50 \cdot \sin(0.02 \cdot t)$, $T_z = 50 \cdot \sin(0.01 \cdot t)$, $M_x = 0$, $M_y = 5 \cdot sign(\sin(0.2 \cdot t))$, $M_z = 22 \cdot \sin(0.1 \cdot t + \pi)$, which created by UV propulsive system.

The simulation was performed with zero initial conditions of UV and observers. Defects in the sensors were simulated by a step change of signals which began at time t = 3 s. Fig. 1 shows the graphs of the 4th, 5th and 6th vector L elements, when in the defect $d\psi$ was introduced.

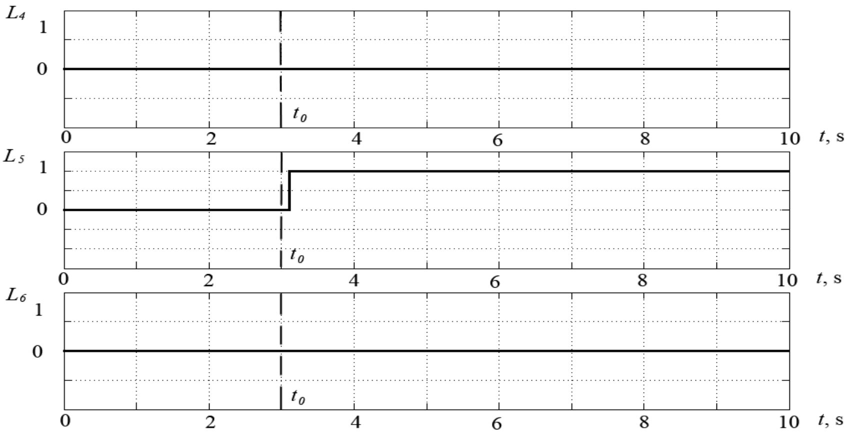

Fig. 1. System response to the introduction of the fault.

As can be seen from the Fig.1 synthesized diagnostic system not only discovered the defect, but also correctly localized. Similar results were obtained in the simulation cases of other types of faults. Thus, the results of mathematical modelling is fully confirmed the efficiency and high performance of the proposed synthesis method of diagnostic systems for typical defects in the navigation sensors of UVs.

5. Conclusion

In this paper, we propose an effective method for the synthesis of high-quality diagnostic systems to frequently occurring types of faults in the navigation sensors of UVs. Proposed system are synthesized by using kinematic model of UVs and data fusion of sensors signals and allows detecting and isolating faults in sensors of UVs at performance of underwater missions in unknown environment with unknown external disturbances.

The research of the obtained systems confirmed the high quality of the diagnosis procedure. It allows to identify and locate defects in these devices well-timed, operatively fend off their effects, to prevent the occurrence of extraordinary events, stopping execution process, the failure of the mission, or loss of UV. This problem can be solved with the help of the so-called method of accommodation to defects. These systems provide additional control signals for the engines. This provides independence of movement of the UV to faults, which ensure the continued working capacity and effectiveness. Development of a method for synthesis of accommodation systems will be a natural subject of further research.

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