Design and investigation of dead reckoning system with accommodation to sensors errors for autonomous underwater vehicle

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Abstract—**This paper considers an approach to creation of reliable dead reckoning system (DRS) for autonomous underwater vehicle (AUV) with accommodation to incorrect sensors information. Proposed DRS is based on using of diagnostic observers built with the help of kinematic model of AUV and special navigation data fusion. The proposed system advantage consists in the relative simplicity of implementation and high accuracy compensation of errors detected in the navigation sensor data. Results of marine trials using the AUV MARC are presented in the paper.**

Keywords - diagnostic system, underwater vehicles, sensor data.

I. INTRODUCTION

The basis of the navigation system of AUV is usually the dead reckoning system (DRS) [1], which includes Doppler velocity log /DVL/ for measuring of linear velocity relative to the bottom surface along two axes of coordinate system connected with the AUV and orientation sensor of AUV measuring the angles of roll, pitch and heading. The current position of AUV is determined by calculating the velocity components and their integration. Errors in sensor data are accumulated in the dead reckoning process and lead to errors in determining of the AUV position.

The use of accommodation methods for automatic detection and correction of sensor data during their underwater work is one of the promising ways for the accuracy and reliability of the DRS elements increasing. The paper describes the approach to the synthesis of the reliable dead reckoning system and some experimental results of the system operation on-board of AUV MARC for magnetic compass errors compensation.

II. DESCRIPTION OF THE ACCOMMODATION METHOD FOR DISTORTED NAVIGATION SENSORS DATA

Now, the several approaches for problem solution of continuous accommodation to the sensor errors are known. These approaches and methods are based on using of diagnostic observers synthesized with the help of nonlinear dynamical model of AUV [2-5].

In this paper, we use the method of the system synthesis for AUV sensor data accommodation proposed in [6]. This method is based on kinematic model of the AUV and special data fusions obtained from onboard navigation sensors. It provides relatively simple practical realization and relatively high compensation accuracy of detected errors.

The considered accommodation method of the system synthesis is comprises of three stages. At the first stage the bank of diagnostic observers (O1-O5) is constructed, which are described by the following models, using the AUV kinematic equations:

$$
\begin{aligned}
&O_1: \dot{\bar{x}} = J_{11}(\tilde{\theta},\tilde{\psi})\tilde{v}_x + J_{12}(\tilde{\varphi},\tilde{\theta},\tilde{\psi})\tilde{v}_y + J_{13}(\tilde{\varphi},\tilde{\theta},\tilde{\psi})\tilde{v}_z,\\
&O_2: \dot{\bar{y}} = J_{21}(\tilde{\theta},\tilde{\psi})\tilde{v}_x + J_{22}(\tilde{\varphi},\tilde{\theta},\tilde{\psi})\tilde{v}_y + J_{23}(\tilde{\varphi},\tilde{\theta},\tilde{\psi})\tilde{v}_z,\\
&O_3: \dot{\bar{\varphi}} = \tilde{\omega}_x + J_{45}(\tilde{\varphi},\tilde{\theta})\tilde{\omega}_y + J_{46}(\tilde{\varphi},\tilde{\theta})\tilde{\omega}_z,\\
&O_4: \dot{\bar{\theta}} = J_{55}(\tilde{\varphi})\tilde{\omega}_y + J_{56}(\tilde{\varphi})\tilde{\omega}_z,\\
&O_5: \dot{\bar{\psi}} = J_{65}(\tilde{\varphi},\tilde{\theta})\tilde{\omega}_y + J_{66}(\tilde{\varphi},\tilde{\theta})\tilde{\omega}_z,
\end{aligned}
\tag{1}
$$

where $[\bar{x},\bar{y},\bar{\varphi},\bar{\theta},\bar{\psi}]^{\mathrm{T}}$ is a state vector of observers; symbol «~» means the signals received from sensors of AUV and can contain errors; $\tilde{v}_z$ is AUV linear velocity along the Z axis in joint coordinate system(JCS); $[\tilde{\omega}_x,\tilde{\omega}_y,\tilde{\omega}_z]^{\mathrm{T}}$ is a vector of angular speeds of AUV in JCS, measured by sensor of angular speeds; J_{ij} ($i,j=\overline{1,6}$) is corresponding elements of matrix $J(\eta)$:

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

where

$$J_{1}(\eta)=\begin{bmatrix} \cos\psi\cos\theta & \begin{matrix}-\sin\psi\cos\varphi+\\+\cos\psi\sin\theta\sin\varphi\end{matrix} & \begin{matrix}\sin\psi\sin\varphi+\\+\cos\psi\cos\varphi\sin\theta\end{matrix} \\ \sin\psi\cos\theta & \begin{matrix}\cos\psi\cos\varphi+\\+\sin\varphi\sin\theta\sin\psi\end{matrix} & \begin{matrix}-\cos\psi\sin\varphi+\\+\sin\theta\sin\psi\cos\varphi\end{matrix} \\ -\sin\theta & \cos\theta\sin\varphi & \cos\theta\cos\varphi \end{bmatrix},$$

$$J_2(\eta)=\begin{bmatrix} 1 & \sin\varphi\tan\theta & \cos\varphi\tan\theta \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \dfrac{\sin\varphi}{\cos\theta} & \dfrac{\cos\varphi}{\cos\theta} \end{bmatrix}.$$

Detection of incorrect data from the sensors is fulfilled by use of the observers bank (1) and a special error matrix D, defining the relationship between the observer values and the signals coming from specific sensors.

In this case, the error matrix will look like the following:

$$D=\begin{array}{c} \\ r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \end{array}\begin{array}{c} \begin{matrix} d\theta & d\psi & dv_x & dv_y & d\omega_x & d\omega_y & d\omega_z \end{matrix} \\ \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \end{array}.$$

Vector I is used for further localization (determining the specific sensor) of detected errors:

$$I=\begin{bmatrix} I_1 & I_2 & \ldots & I_5 \end{bmatrix}^{\mathrm{T}},\ I_k=\begin{cases} 1, & \text{if } |r_k|>r_{k0} \\ 0, & \text{if } |r_k|\le r_{k0} \end{cases},$$

where value r_{k0} determines the threshold of observer sensitivity ($k=\overline{1,5}$).

Next, compare vector I and columns of error matrix D to obtain a vector $L=[L_1 \quad L_2 \quad L_3 \quad L_4]^T$:

L_1=1, if I=D^1; L_2=1, if I=D^2; L_3=1; if I=D^3 or I=D^4; L_4=1, if I=D^5 or I=D^6 or I=D^7;

where D^l is l-th column of matrix D ($l=\overline{1,7}$).

All the elements of the vector L will be zero in the absence of errors. If an error occurs in determining of the pitch angle then first element of vector L becomes equal to 1 and the rest elements are zero. Second, third and fourth elements of the vector L correspond to the errors in the heading, DVL and angular velocity sensor data.

After detecting of faults, which occurring in the sensors, it is necessary to identify accurately the magnitudes of these faults in real time.

In the last phase of fault tolerant system synthesis the additional signals are generated in the AUV control systems to eliminate the errors. To solve this problem the vector of calculated fault values R is used:

$$R=[L_1 d\theta, L_2 d\psi, L_3 dv_x, L_3 dv_y, L_4 d\omega_x, L_4 d\omega_y, L_4 d\omega_z]^T. \quad (2)$$

In the event of a fault d_l, there will be vector R in the diagnosis system output, where the l-th element is equal to the value of the fault and the rest elements are zero. All elements of the vector will be zero in the absence of faults. Next, the obtained values of errors are subtracted from the actual sensor signals to obtain corrected values required for AUV proper positioning:

$$[\theta,\psi]=[\tilde{\theta}-R_1,\tilde{\psi}-R_2],\ [v_x,v_y]=[\tilde{v}_x-R_3,\tilde{v}_y-R_4],$$
$$[\omega_x,\omega_y,\omega_z]=[\tilde{\omega}_x-R_5,\tilde{\omega}_y-R_6,\tilde{\omega}_z-R_7]. \quad (3)$$

III. The AUV MARC on-board realization of DRS with accomodation

The system (1-3) with accommodation was used for designing of DRS for AUV MARC navigation system. AUV MARC /Marine Autonomous Robotic Complex/ (fig. 1) was built in Scientific Education Center “Underwater robotics” /SEC UR/ based on Far Eastern Federal University /FEFU/ and Institute for Marine Technology Problems Far Eastern Branch of Russian Academy of Sciences /IMTP FEB RAS/ [7].

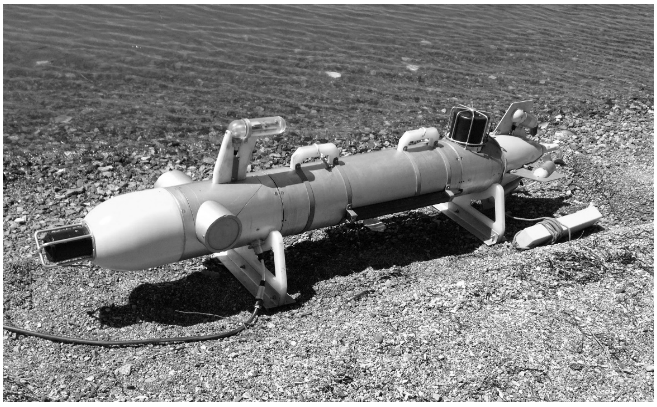

Fig. 1. Small AUV MARC.

The DRS for AUV MARC includes the sensor for roll, pitch and heading angles and angle velocities, DVL and depth meter. The Inertial Measurement Unit /IMU/ Mti Xsens (Xsens Technologies) was used for roll, pitch and heading angles and angle velocities measurement. It includes 3D magnetometer, 3D accelerometer with scale up to 5g and three gyros intended for angle velocities measurement up to 300°/sec. The sensor data processing is fulfilled on base of embedded micro controller using the Extanded Kalman Filter /EKF/.

DVL Explorer (Teledyne RD Instrument) with measurement error 0.2% ± 1 mm/sec is used as absolute velocity log. Citadel CTD (Teledyne RD Instrument) is used for depth, temperature and conductivity measurements. Its error in depth measurement is about 0.1 m and maximum operational depth – 500 m.

IV. Some results of the marine trials for DRS with accomodation no board of AUV MARC

The marine trials of modernized DRS with accommodation were organized on board of AUV MARC in 2014 in Novik Bay of Russki Island (fig. 2). The designed system was solving the task of heading sensor error compensation based on angular velocity data.

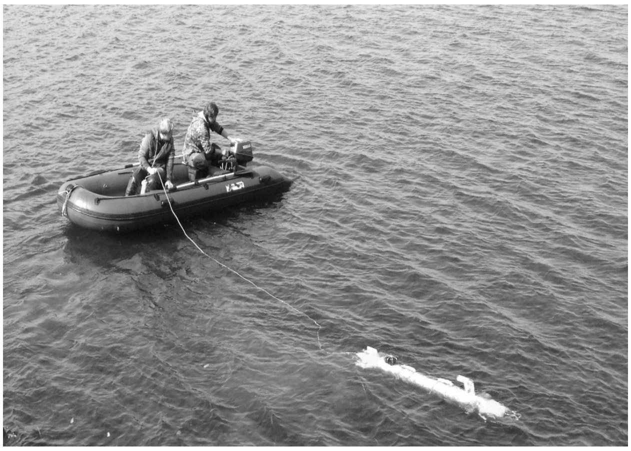

Fig. 2. Execution of the experiment.

The same AUV mission was used in the experiments – motion along the sides of square with length of 50 m, depth of 2 m and velocity of 1 m/sec. First tack was executing with heading to the North and each next tack turned 90 degrees right. The origin of coordinate system was accepted in the start point of AUV trajectory. The first side of square was executed two times to receive four AUV turns.

There were used three modes of DRS accommodation module operation:

1. Transparent mode. DRS accommodation module just retransmit the data from on-board sensors.

2. Error generation mode. DRS accommodation module changes the data from pointed sensor by program (generation of fixed value, adding of fixed value to initial data, adding of variable value to initial data).

3. Error generation and correction mode. DRS accommodation module changes the data from pointed sensor by program and then corrects it by accommodation system.

In the second and third modes the DRS accommodation module operates with modified navigation sensor data. For real AUV motion trajectory calculation the post processing is fulfilled based on real navigation data collected in the DRS accommodation module.

Some results of DRS accommodation system operation on-board of AUV MARC during marine trials are represented on fig. 3 – 5. On fig. 3 the results of system operation are shown when the data from heading sensor were distorted by adding of constant error of 1 rad, on fig. 4 we can see the system operation when the data from heading sensor were distorted by adding of sinusoidal error described by sin (0,05t) and on fig. 5 the results of system operation are shown with fault constant signal of 1 rad from heading sensor instead of real data. Three curves are presented on the pictures. Program AUV trajectory is denote by number 1, curve 2 shows the AUV trajectory with errors in heading sensor and curve 3 - AUV trajectory after correction calculated by DRS accommodation system.

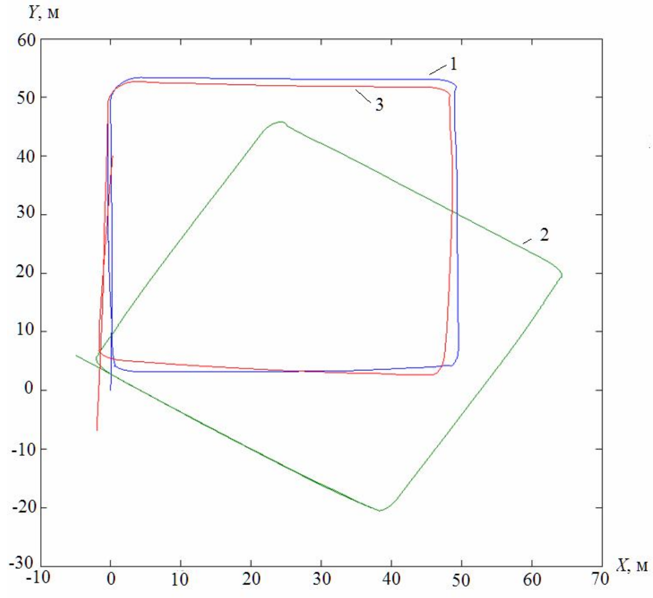

Fig. 3. The trajectory of the AUV with constant error of heading sensor.

From fig. 3 we can see that the constant error in heading sensor signal leads to AUV trajectory turning for angle equals to the constant error. The AUV trajectory deviation from desired trajectory for distance of 50 meters can reach up to 20 meters. Fig. 4 and 5 show that variable error or fault in the AUV heading sensor lead to loose of AUV capacity for work - the vehicle trajectory of motion becomes unpredictable. Nevertheless in all cases the correction calculated by DRS accommodation system provides the AUV motion along the program trajectory with dynamic error that does not exceed four meters.

In this way the analysis of experimental results allows to make conclusion that the designed DRS with accommodation provides the AUV motion along the program trajectory even for big errors in heading sensor or its fault. The absence of DRS with accommodation leads to loose of AUV capacity for work.

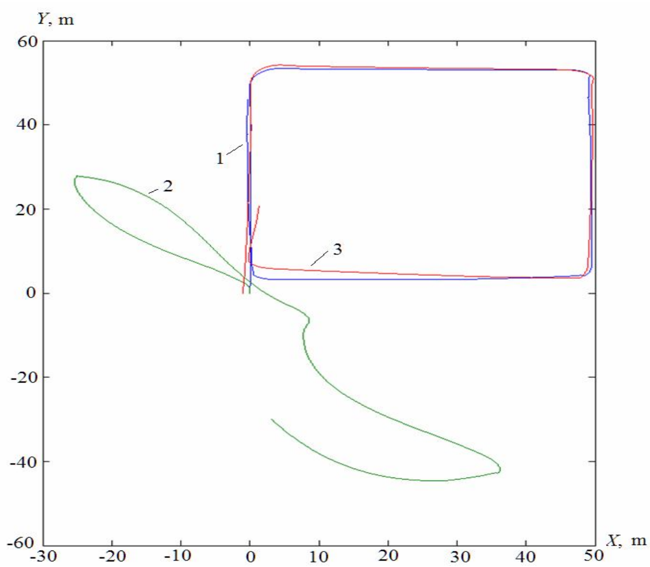

Fig. 4. The trajectory of the AUV with sinusoidal errors of heading sensor.

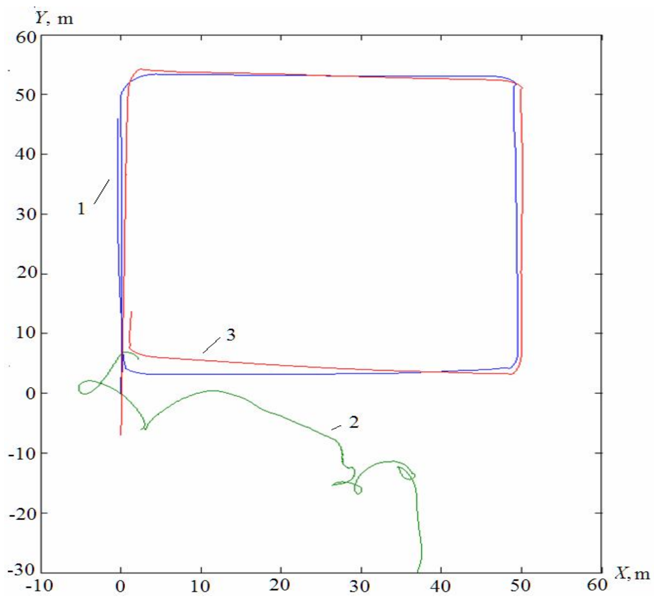

Fig. 5. The trajectory of the AUV with fault constant signal from heading sensor.

V. CONCLUSIONS

The approach to the designing of the DRS with accommodation to error data for AUV MARC on-board navigation sensors based on the use of kinematic model of AUV and special fusion of navigation data was described. Implementation of the proposed algorithm of accommodation was performed by introducing an additional program module for the collection and processing of information from navigation sensors. The correction of error data from heading sensor on-board AUV was performed using three different error models. The experimental results confirm the workability and effectiveness of the proposed DRS with accommodation.

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