CONTROL SYSTEM FOR UNDERWATER VEHICLE WITH MULTILINK MANIPULATOR FOR AUTOMATIC MANIPULATION OPERATIONS

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Abstract

This paper describes development and research of the new synthesis method of control system for autonomous and remotely controlled underwater vehicles and for multilink manipulators mounted on the vehicles. Such system admits to realize widely used underwater research manipulation operations in automatic mode. Some of them are: collecting bio-organisms, definition of composition and density of the soil with special probes and drills, taking precipitation samples with hermetically sealed soil tubes, measurements with thermistor sensors in different layers of sedimentary soil.

Keywords: underwater vehicles; multilink manipulators; Doppler lag; automatic mode; manipulation operations.

1. Introduction

The problem of automatic implementation of different manipulation operations types in the depths of the Global Ocean is very topical nowadays. Many researchers successfully solve problems of the underwater vehicles (UV) development. These UV are equipped with one or several multilink underwater manipulators (UM) [1-3]. Such systems are designed to carry out many technological and research operations. Field of its application is significantly expanding by means of realization of new kinds of operations.

The manipulator-equipped UV are the mostly used for research operations in hydrogeology, hydrobiology, geophysics, hydrochemistry, in oil and gas extraction. The next operations are carried out in these cases: 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.

In most cases, specially trained operators implement these operations in manual mode. However, it is very complicated to solve such tasks quickly and accurately without direct contact with work object (WO) and with knowing its location from the video picture only. Furthermore, there are only known single cases of using the autonomous UV for the simplest manipulation operations in automatic mode [3].

Nowadays, control systems for navigation and automatic movement of UV have been already developed and investigated [4, 5]. Methods and approaches that guarantee high precision holding of the UV near WO have been also developed [6-9]. It allows fixing the UV in the determined spatial point with desired spatial orientation and without grounding and roiling of near-bottom layers. Moreover, described in the paper [10] correction method of UM movement trajectories allows to carry out the manipulation operations even in conditions of unplanned displacements of the UV relative to WO.

The most important part of solving of manipulation tasks in automatic mode is the definition of the location and spatial orientation of the WO relative to the UV. In addition, it is the formation of special motion modes of UM and the UV, at which the task is to be solved with prescribed accuracy and without emergencies. Paper [3] offers the special markers fixation on WO that allows to define location of WO and its orientation relative to the UV. Also video picture processing algorithms are used in this paper to carry out the special operations of carbine capture of WO with previously known form and colour. In paper [11] the processing algorithms of video streams from several cameras are used in cases of complicated forms of WO. Previously installed light markers are also used in this paper.

However, it is impossible to install markers near the seabed surface during the implementation of underwater research operations. Form and colour of this surface do not allow to use video processing algorithms effectively. As a result, features and disadvantages of known approaches do not allow to automatize the implementation of widely used operations in the depths of the Global Ocean.

Creating of the effective approaches for solution of stated manipulation tasks in automatic mode allows to use the autonomic UV equipped with UM with expanding of vehicles functionality and reducing of the underwater works cost. In addition, automatization of UM allows to improve quality and increase the speed of operations, performing by the remote operated UV. The operator's psychological load, obviously, decreases.

2. Formulation of the problem

The task of development of the new approach for automatic performing of research manipulation operations by the UV equipped with UM near the seabed surface is set. Location of WO or seabed surface relative to the UV should be defined using onboard sensors during the realization of this approach. Also the UV movement control for the most convenient position assignment for performing of operation is used. Movement trajectories of working instruments of multilink UM should be formed considering the boundaries of the UM workspace and the information about model of WO. Along these trajectories, UM should affect the least possible force and torque effects on the UV.

3. Definition of the UV and seabed surface interposition

It is necessary to determine the location and spatial orientation of WO in real time scale to solve the manipulation tasks in automatic mode during entering of UV into the workspace. During implementation of research underwater operation, seabed surface serves as the WO. By deep-sea researches in hydrogeology, hydrobiology, geophysics and hydrochemistry using the UV in Sea of Japan, Sea of Okhotsk, Bering Sea, Chukchi Sea and the Pacific Ocean, it has been shown that in most cases seabed surface has only small roughness. That is why research manipulation operations, which are related to sampling of soil probes of sediment layers, are implementing in conditions of bottom low relief. In addition, seabed surface with sufficiently low relief can be tilted about the horizontal plane. This complicates entering of the UV into the workspace and implementation of manipulation tasks.

In condition of the UV nearness to seabed surface, this surface can be approximately described as a plane and its spatial orientation relative to the UV can be determined.

Advanced absolute Doppler lags allow high-precision determination of distance from log to bottom along axes of its hydro acoustic antennas, which usually not less than three. The obtained measurements are translated into right rectangular coordinate system (CS) that rigidly connected with the body of the UV. The origin of coordinates is located in the UV centre of buoyancy C, X^* axis coincides with the roll axis of the UV, Z^* axis coincides with the vertical axis of the UV, Y^* axis is right-handed. As a result, in CS $X^*Y^*Z^*$ we have an array of points, which belong to seabed surface.

It is necessary to approximate the obtained array of points by linear polynomial using least square method to derive the equation of plane. In the general case, equation of plane is written as next one [12]:

$$Ax + By + Cz + D = 0, \quad (1)$$

where A, B, C, D are the constant coefficients, and A, B, C are not equal to zero simultaneously. After transformations, (1) is given by:

$$z = A^* x + B^* y + C^*, \quad (2)$$

where $A^* = -\frac{A}{C}$, $B^* = -\frac{B}{C}$, $C^* = -\frac{D}{C}$.

According to least square method, it is necessary to determine parameters A^*, B^*, C^* such that the next conditions are implementing:

$$\sum_{i=1}^n e_i^2 = \sum_{i=1}^n [z_i - z(x_i, y_i)]^2 \rightarrow \min, \quad (3)$$

where x_i, y_i and z_i are the coordinates of points in the array of measurements; $z(x_i, y_i) = A^* x_i + B^* y_i + C^*$; $\sum_{i=1}^n e_i^2$ is the sum of squared deviations; $i = \overline{(1, n)}$, where n is the number of points in the array of measurements. To solve the problem of function (3) minimizing it is necessary to find its critical points, differentiating it with respect to unknown parameters A^*, B^*, C^* , setting derivatives to zero and solving obtained system of equations:

$$\begin{cases} \frac{\partial \sum_{i=1}^n e_i^2}{\partial A^*} = \frac{\partial \sum_{i=1}^n [z_i - A^* x_i - B^* y_i - C^*]^2}{\partial A^*} = 0, \\ \frac{\partial \sum_{i=1}^n e_i^2}{\partial B^*} = \frac{\partial \sum_{i=1}^n [z_i - A^* x_i - B^* y_i - C^*]^2}{\partial B^*} = 0, \\ \frac{\partial \sum_{i=1}^n e_i^2}{\partial C^*} = \frac{\partial \sum_{i=1}^n [z_i - A^* x_i - B^* y_i - C^*]^2}{\partial C^*} = 0. \end{cases} \quad (4)$$

The modified (4) is given by:

$$\begin{cases} A^* \sum_{i=1}^n x_i^2 + B^* \sum_{i=1}^n x_i y_i + C^* \sum_{i=1}^n x_i = \sum_{i=1}^n z_i x_i, \\ A^* \sum_{i=1}^n x_i y_i + B^* \sum_{i=1}^n y_i^2 + C^* \sum_{i=1}^n y_i = \sum_{i=1}^n z_i y_i, \\ A^* \sum_{i=1}^n x_i + B^* \sum_{i=1}^n y_i + n C^* = \sum_{i=1}^n z_i. \end{cases} \quad (5)$$

Solving the system using Cramer's rule [13], we find unknown A^*, B^*, C^* :

$$\Delta = \begin{vmatrix} \sum_{i=1}^n x_i^2 & \sum_{i=1}^n x_i y_i & \sum_{i=1}^n x_i \\ \sum_{i=1}^n x_i y_i & \sum_{i=1}^n y_i^2 & \sum_{i=1}^n y_i \\ \sum_{i=1}^n x_i & \sum_{i=1}^n y_i & n \end{vmatrix} \neq 0, \quad \Delta_1 = \begin{vmatrix} \sum_{i=1}^n z_i x_i & \sum_{i=1}^n x_i y_i & \sum_{i=1}^n x_i \\ \sum_{i=1}^n z_i y_i & \sum_{i=1}^n y_i^2 & \sum_{i=1}^n y_i \\ \sum_{i=1}^n z_i & \sum_{i=1}^n y_i & n \end{vmatrix} \neq 0, \quad (6)$$

$$\Delta_2 = \begin{vmatrix} \sum_{i=1}^n x_i^2 & \sum_{i=1}^n z_i x_i & \sum_{i=1}^n x_i \\ \sum_{i=1}^n x_i y_i & \sum_{i=1}^n z_i y_i & \sum_{i=1}^n y_i \\ \sum_{i=1}^n x_i & \sum_{i=1}^n z_i & n \end{vmatrix} \neq 0, \quad \Delta_3 = \begin{vmatrix} \sum_{i=1}^n x_i^2 & \sum_{i=1}^n x_i y_i & \sum_{i=1}^n z_i x_i \\ \sum_{i=1}^n x_i y_i & \sum_{i=1}^n y_i^2 & \sum_{i=1}^n z_i y_i \\ \sum_{i=1}^n x_i & \sum_{i=1}^n y_i & \sum_{i=1}^n z_i \end{vmatrix} \neq 0,$$

$$A^* = \frac{\Delta_1}{\Delta}, B^* = \frac{\Delta_2}{\Delta}, C^* = \frac{\Delta_3}{\Delta}.$$

As a result, (2) with parameters from (6) will be equation of plane, which characterizes the spatial orientation of seabed surface near the UV.

4. Approach of the UV with predetermined spatial orientation to WO

During automatic entering of the UV into workspace it is necessary that roll axis X^* of the UV is directing to the rise of the plane, because workspaces of UM, which are installed on the UV, are located in the front semisphere of these vehicles. Also sensors, cameras, lights and other equipment are concentrated at the front of the UV. For the UV attitude control it is necessary to control the UV roll and trim angles. But it will cause additional energy demands because stability of the well-ballasted UV tends to reset roll and trim angles to zero.

Besides, propulsion system of many UV of survey and working classes does not allow to control roll and trim angles, that is why such UV should be directed to the rise of seabed surface. It lets to carry out survey, searching and manipulation operations in the condition of bottom rugged relief.

It should be mentioned that UV direction to the rise of seabed surface allows to see the bottom in time with preventing of emergencies. Also this direction allows to move the UV up and down inclined with permanent visual contact with seabed surface.

To satisfy a mentioned condition it is necessary to direct the UV along the vector $\bar{n}^*$ direction. This vector is the projection of the plane normal vector $\bar{n} = [A, B, C]^T \in R^3$, which is described by (2), on plane CX^*Y^* of CS $X^*Y^*Z^*$ (see Fig. 1).

Fig. 1. Determination of the UV orientation

Using the vector $\bar{n}^* = [A, B, 0]^T \in R^3$ and the vector of roll axis of the UV $x^* = [1, 0, 0]^T \in R^3$, desired angle θ can be defined by the next equations:

$$\theta = \arccos \left(\frac{\bar{n}^* \cdot x^*}{\|\bar{n}^*\| \|x^*\|} \right) \text{ if } B > 0;$$

$$\theta = -\arccos \left(\frac{\bar{n}^* \cdot x^*}{\|\bar{n}^*\| \|x^*\|} \right) \text{ if } B < 0;$$

It is obvious that after rotation by angle θ relative to Z^* axis of CS $X^*Y^*Z^*$ roll axis Y^* of UV will be directed to the rise of seabed surface.

Doppler lags allow to update the array of points of seabed surface in CS $X^*Y^*Z^*$ several times per second. Therefore the plane equation (2) of seabed surface for current Doppler lag measurements should be defined during process of the UV movement and the UV stabilization in hang mode. It allows to use actual information about location and orientation of seabed surface for control of the UV and the UM movements.

5. UV trajectory formation

We consider approach for formation of UM working tool movement trajectory by the example of implementation of widely used underwater research operation of taking precipitation samples with hermetically sealed soil tubes. Sampler that configured as a tube with a reverse valve at the upper end is fixed in UM working tool for the sampling of a soil. Process of the soil sampling consists in immersing of tube perpendicular to seabed surface at least at $2/3$ of length into soil, and then sampler is getting out and move to the transportation position.

The method for calculation of UM working tool movement trajectory for implementation of determined manipulation operation is further described.

For simplification of calculation of interposition of the UM and calculated seabed plane (2), workspace of UM is proposed to be represented as finite numbers s of segments inserted in it. These segments are parallelepiped-shape with equal bases. Vertical axis of described segments are parallel to the axis Z^* of CS $X^*Y^*Z^*$.

Divided into segments workspace of UM is shown at Fig. 2. In this figure the next labels are introduced: 1 is the seabed surface, 2 is the plane approximating the seabed surface, 3 is the approach point P_a of the UM working tool, 4 is the sampler, 5 is the point C_a of intersection of the segment vertical axis with the seabed surface 2. Number of segments is chosen because of workspace size, measures of sampler and required accuracy of manipulation operation implementation.

Fig. 2. Scheme of manipulation operation

For every segment $a = \overline{(1, s)}$ coordinates x_{ca} and y_{ca} of its vertical axis and X^*Y^* plane crossing are known. The point C_a is a crossing of vertical axis of segment a and seabed surface plane. Using (2), let's find coordinate z_{ca} of crossing point C_a using the formula:

$$z_{ca} = z(x_{ca}, y_{ca}) = A^* x_{ca} + B^* y_{ca} + C^*.$$

For the gained point C_a with coordinates (x_{ca}, y_{ca}, z_{ca}) let's find the approach point P_a on the perpendicular to plane (2) using the formula:

$$P_a = C_a - \frac{\bar{n}}{\|\bar{n}\|} l,$$

where l is a length of a sampler. Every calculated point P_a is checked for belonging to UM workspace.

For minimization of force and torque effects on UV from moving UM, lever from working tool to UV center of mass should have minimal length during the immersion of a tube into the soil. For that, from all belonging to UM workspace points P_a one point with the closest to point C of CS $X^*Y^*Z^*$ distance is chosen.

As a result, a trajectory of UM movement could be represented as a sequence of working tool transition from initial position to approach point P_a and then to C_a , in which sampler has the deepest soil immersing. After that the working tool firstly moves through P_a and then returns to initial position.

It should be mentioned that in case of no points C_a in workspace of UM, UV should keep immersion, and in case of no points P_a in workspace, UV should perform a re-entry into the work area.

6. Conclusion

In this paper the synthesis method of control system for automatic implementation of underwater research manipulation operations by means of UV with UM was developed. Proposed system controls linear and axial movements of the UV to define its best position for manipulation operations. Also this system forms spatial trajectories of the multilink UM working tools taking into account the information about continuously refined spatial location of the bottom surface. These trajectories are formed such that the UM acts the least possible force and torque effects on the UV during the process of operation, taking into account the borders of UM workspace.

The control system for remotely controlled UV and multilink UM mounted on the vehicle has been developed based on the proposed method. Sea tests in deep-sea expedition in Bering Sea with UV Sub-Atlantic Comanche 18 equipped with UM Schilling Orion 7P have been completed for research of operability and features of functioning of synthesized control system. Used UV and UM are shown on Fig. 3. In automatic mode this system defined the location of the bottom surface relative to the UV by means of the onboard Doppler lag. Implemented in software control system improved accuracy and speed of implementation of underwater research operations. Results of experiments approved efficiency and simplicity of practical realization of developed control system of UV and UM for implementation of manipulation operations in automatic mode.

Fig. 3. Sea tests with UV Comanche 18

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