Development and Research of Path-Planning Module for Control System of Underwater Vehicle

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***Abstract*—When underwater vehicle need move from point A to point B during the completion of the mission it can be guided by the remote operator or move by itself. Both ways have pros and cons. For autonomous movement, control system needs a safe path that allows to pass the obstacles at the required speed. In previous papers authors already described the development of the control system, position-path movement method, vehicle mathematical model, development of the hull and simulation results. Continuing this project, current paper is devoted to path planning module for the control system of the underwater vehicle. It briefly references the mathematical model, then describes position-path regulator. It is based upon PD law and implemented in discrete form with calculation of D-component using trapezoid formula. Having control variables a yaw angle and longtitudal velocity, regulator outputs desired rotation speed of water screws. Path planning procedure consists of two steps. At first path is calculated on the basis of A*-algorithm using the known scene part. Then dynamic window method modifies the path so that UV moves at required velocity not passing the obstacles at unacceptable distance. Proposed approach was tested in Simulink app and proved to be efficient even in hard scenes with many obstacles.**

***Index Terms*—control, underwater vehicles, path planning**

I. INTRODUCTION

Modern underwater vehicles can be used for many applications including ecology and climate monitoring, sea exploration, service of submerged systems, search for deposits, protection of water areas and so on. In case of unmanned underwater vehicle, these tasks can be completed more effectively due to reduction of operation cost and error probability (caused by absence of operator), increase of autonomous running time, decrease of mass and dimensions of the object, etc. [1]-[3]. Southern federal university in Russia has a reach history of research, devoted to the Underwater Vehicles (UV). Development of the control system for such a complex object is rather challenging [4]-[6] and one of the hardest parts is mathematical model. It should take into account unsteadiness of parameters, dynamics nonlinearity and multiple connections of the underwater vehicle, as well as consider interaction of hull with viscous fluid and unexpected disturbances [7].

If UV has a requirement to follow precisely along the stated path, especially at high speed and in uncertain operation environment, development of path-planning module for the control system is a task of high importance. Along with the control methods and algorithms, presented earlier [8]-[11] it will allow underwater vehicle to move safely avoiding the obstacles during the mission.

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II. MATHEMATICAL MODEL OF THE UNDERWATER VEHICLE

Two Cartesian coordinate systems (Fig. 1) are used to describe UV mathematical model [7]. Model is based on the solid body equations and can be presented in the vector-matrix form:

$$\dot{\bar{Y}} = \Sigma(\bar{\Theta}, \bar{X}) = \Sigma\begin{pmatrix}\Sigma_{\mathrm{P}}(\bar{\Theta}, \bar{X}) \\ \Sigma_{\Theta}(\bar{\Theta}, \bar{X})\end{pmatrix} \quad (1)$$

$$\widetilde{M}\dot{\bar{X}} = \bar{F}_d(\bar{P}, \bar{V}, \bar{\omega}) + \bar{F}_u(\bar{\delta}) + \bar{F}_v(G, A_p, R_g) \quad (2)$$

$$T_{uy}\frac{d\bar{\delta}}{dt} + \bar{\delta} = \bar{\Psi}_{uy}(\bar{\delta}, \bar{U}) \quad (3)$$

where T_{uy} — diagonal matrix of time constants of the Actuating Devices (AD); $\bar{\Psi}_{\mathrm{uy}}(\bar{\delta}, \bar{U})$ — vector of nonlinear functions of the AD equation right-hand sides; $\bar{\delta}$ — vector of the control actions for UV elements, formed by AD; $\bar{U}$ — control vector, formed by UV control system; m — vector of internal coordinates (state coordinates); M $(m \times m)$ — matrix of mass and inertia parameters that include mass, moment of inertia, added masses of underwater vehicle; $F_u(x, Y, \delta, l)$ — m-vector of control forces and moments and l — vector of construction parameters; $F_d(x, Y, l)$ — m-vector of nonlinear elements of UV dynamics; F_{v} — m-vector of

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measureable and non-measureable external disturbances; $Y = (P, \Theta)^T$ — n-vector of position P and orientation Θ (output coordinates) in body coordinate system in respect of reference coordinate system; $\Sigma(\Theta, x)$ — n-vector of kinematic links; $\Sigma_{\mathrm{p}}(\Theta, x)$ —vector of linear velocities in in body coordinate system in respect of reference coordinate system; $\Sigma_{\Theta}(\Theta, x)$ — vector of angular velocities in in body coordinate system in respect of reference coordinate system;

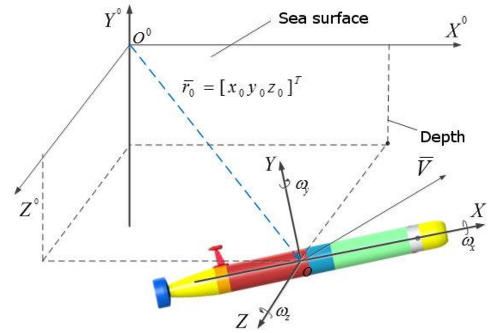

Figure 1. Coordinate systems K(OX0Y0Z0) and K(OX Y Z).

III. Development of the Path Planning System

A. Position-Path Regulator for the Underwater Vehicle

Movement regulator was developed for research of hierarchical UV control system. Regulator is based upon PDlaw and implemented in discrete form with calculation of D-component using trapezoid formula [12].

Regulator output a vector of engine rotation speeds. Control variables — yaw angle and longtitudal velocity. Result vector of the desired rotation speed of water screws is calculated by:

$$w_c = w_{xc} - \frac{w_{zc}}{2} w_{cx} + \frac{w_{zc}}{2} \quad (4)$$

Components in Eq. (4) are defined as follows:

$$w_{xc}(i+1) = k_{p1}\big(V_{x3}(i) - V_x(i)\big) + k_{d1}\big(V_{x3}(i) - V_x(i)\big) - \frac{V_{x3}(i) - V_x(i-1)}{T} \quad (5)$$

$$w_{yc}(i+1) = \sqrt{\frac{g}{4b}} + k_{p2}\big(y_3(i) - y(i)\big) + k_{d2}(y_3(i) - y(i)) - \frac{y_3(i) - y(i-1)}{T} \quad (6)$$

$$w_{zc}(i+1) = k_{p3}(V_{z3}(i) - V_z(i)) + k_{d3}(V_{z3}(i) - V_z(i)) - \frac{V_{z3}(i) - V_z(i-1)}{T} \quad (7)$$

where i — number of step in control action calculation procedure; k_{pj}, k_{dj}, j = 1, 2, 3 — coefficients of proportional and differential components; V_{X3}, V_{Z3} — projections of the desired movement velocity, calculated by regulator; V_X, V_Z — projections of the movement velocity; y_3 — stated UV depth; T — sampling frequency.

During the movement along the stated path, regulator determines the projections of the desired velocity by the following equation:

$$V_3 = [V_{max}\cos(\varphi)\ 0\ V_{max}\sin(\varphi)] \quad (8)$$

where φ — angle between $0X$ axis and line, connecting origin of coordinates with next path point; $V_{\max}$ — maximum UV velocity.

When slowing down in neighbour of the goal point, V_{X3} projection of the desired speed is determined by the Eq. (9). Value for the V_{Z3} is calculated by analogy.

$$V_{3x} = \frac{V_{max}\cos(\varphi) sgn(x_3 - x)}{1 + e^{-ax+b}} \quad (9)$$

where a, b — parameters that define the form of the exponent function.

B. Movement Path Planning

A two-step approach was developed for the calculation of the path with reference to the limitations for the underwater vehicle movement. It consists of algorithm and modified method of dynamic window [13]. Optimal trajectory is constructed by A*-algorithm [14] using known scene part. Then dynamic window method modifies the path so that UV moving at maximum velocity and not passing the obstacles at unacceptable distance.

Procedure of path planning based on A*-algorithm is as follows. First, map of the area is created. Movement scene is divided into square cells. Each cell is assigned a value that describes it as free, occupied by the obstacle, start and goal (finish). At first, all cells are considered to be free, but then, using radar, data map updates. Algorithm starts each time when the value of the cell in the path is modified or when the desired movement parameters are changed.

Safety of moving along the path is provided by marking the cells around the obstacle as occupied. Number of such cells with "virtual obstacles" are defined by cell size and minimum allowed distance between UV and the obstacle. In order to prevent UV trapping into local minimum, cells that UV visits several times are marked as occupied.

After generation or update of the map, two lists of cells are made. First list, named "open" is filled by the cells for which it is necessary to calculate the length of the UV path. The second list, named "closed" is filled by the cells for which this length is already calculated.

Then algorithm reviews the cell, where the UV is positioned now and surrounding eight cells (see Fig. 2)

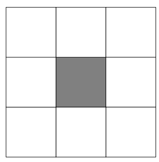

Figure 2. Block of cells — candidates for entering the "open" list.

Starting cell is added to the "open" list. Then it is necessary to check all surrounding cells. They are added to the "open" list if contain no obstacles or placed out of the scene boundaries. For every newly added cell coordinates of the previous cell (also called parent) are recorded and efficiency function f (showing the length of the path through this cell) is calculated. Starting cell is added to the "closed" list. Then we take cell from the "open" list with the minimum f and so on.

Efficiency function is calculated by equation:

$$f=g+h \tag{10}$$

where g — cost of UV transfer from starting point to the current point, h — cost of UV transfer from the current cell to the goal point.

Value g is a sum of cost to transfer UV from the starting point to parent point and cost of transfer from the parent cell to the current one. For example, for the cells in Fig. 3 let's assume that cost of transfer from the center cell to the cell with horizontal or vertical shift is 10. And cost of transfer to cell with diagonal shift is 14.

Value h is a cost of transfer (horizontal or vertical) between current and goal cells, equal to "number of cells to go"x10.

A*-algorithm for path-planning consists of the following steps:

1. Add staring cell to the "open" list.
2. Repeat steps a) to d).
   a. Search the "open" list for the cell with minimum value of *f*. Mark the found cell as current.
   b. Add current cell to the "closed" list and remove it from the "open" list.
   c. For every 8 surrounding cells do:
      i. If considered cell contains the obstacle and it is in the "closed" list, it is ignored.
      ii. Add cell to the "open" list (if not already there). This cell becomes a parent for the current cell. Calculate values of *f*, *g*, *h* for the considered cell.
      iii. If cell present in "open" list, then check path length through this cell using *g* value. Lower *g* value corresponds to the shorter path. The cell with lowest *g* becomes parent for the considered. Recalculate *g* and *f*.
   d. Stop the algorithm if goal point found in the "open" list (path is ready) or "open" list is empty and foal point not reached (path is impossible).
3. Save the path.

IV. Simulation

Simulation results for UV movement for multiple scenes considering dynamic limitations are presented in Fig. 3.

Simulation was conducted in Simulink app. Obstacles, marked as circles were places on the flat square scene with dimensions 25x25 meters. Starting point was set to (0, 0) and goal point to (20, 20) for every case. Several types of obstacles were used (from easy to hard):

- Type 1 — single (circle),
- Type 2 — corner "┐",
- Type 3 — half rectangle "⊔".

Blue line is a path, calculated by the planning module. In this simulation, UV was considered to be a single point with no volume. Allowable obstacle passing distance was to 2 meters.

Simulation showed that planning module manages easily with number of single obstacles (Fig. 3a) Vehicle passed them in a "snake" manner. Addition of one type 2 and one type 3 obstacle aside the path (Fig. 3b) didn't confuse the planner and it successfully avoided hard obstacles. Placing type 2 obstacle in front (Fig. 3c) slowed it down (see the loop), but it found the way out. The hardest scene (Fig. 3d), however, was a fail. Vehicle was trapped inside the type 3, half rectangle, obstacle.

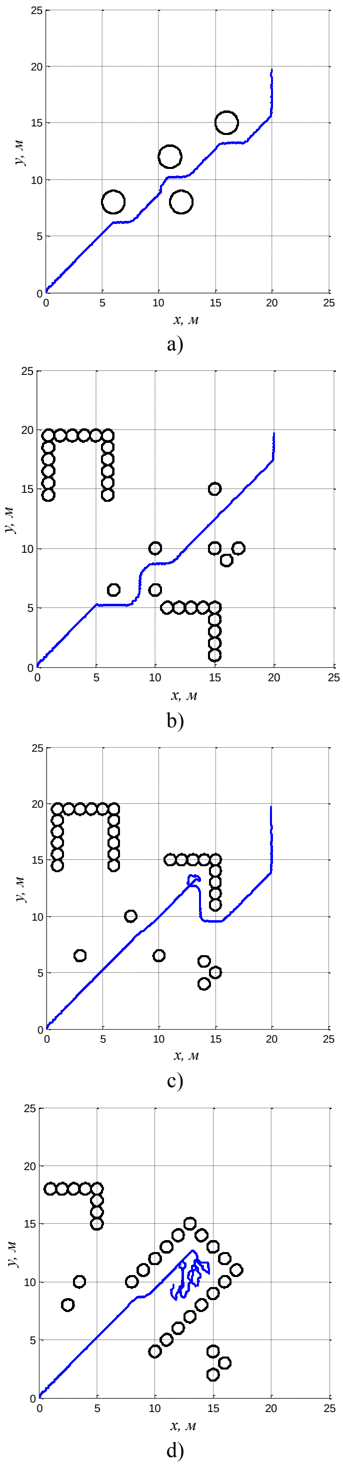

Figure 3. UV path for various scenes.

V. CONCLUSION

Path planning approach, proposed in this paper is based on A*-algorithm and modified method of dynamic window. It is intended for the intelligent underwater vehicles and allows to move in known environment avoiding the obstacles. Calculated path considers required velocity by specifying minimum obstacle passing distance. Simulation results showed strong and weak sides of described approach. Utilized hybrid method for horizontal and vertical movement allows underwater vehicle to reach the goal even in hard scenes, but cannot manage "⊔"-like obstacles where operator override is necessary. In the next paper, this approach should be extended from flat to three-dimensional scenes and modified to manage more types of obstacles.

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