Motion Control Model and HUV Dynamics for Patrolling Sea Areas with Complex Bottom Topography

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Abstract. The Patrolling sea areas is one of the main tasks of the HUV when performing both typical search and survey works and a number of special-purpose works when servicing marine infrastructures [1]. The task of patrolling includes a purposeful choice of the route of the HUV with the search and examination of objects (targets), which implies the use of effective control under conditions of uncertainty in the environment and a correct dynamic model of movement, taking into account possible errors in the initial data. Particularly difficult is the task of realizing the spatial movement of the HUV near the bottom with a variable relief and the presence of significant obstacles along the route of movement. In the general case, it is required to provide equidistant movement relative to the bottom with safe overcoming of obstacles and minimization of traffic costs [2]. The solution to the problem depends on the effectiveness of the executive bodies (propulsion and steering complex) and obstacle detection equipment (echolocation systems for forward and downward vision). The control algorithm is based on multi-channel rangefinder information to obstacles and the angular orientation of the AUV relative to the bottom topography profile. The structural and hydrodynamic characteristics of the hybrid vehicle obtained in [3] are used in the model of the dynamics of the HUV. The report presents the results of research on the issues under consideration based on modeling dynamic processes using software tools Simulink Matlab, StateFlow Simulink and available experimental data.

1. Presentation of raw data

When setting the task of patrolling the sea area, it is necessary, first of all, to determine the nature of the bottom relief and the corresponding means for controlling the motion of the HUV along equidistant trajectories at a given distance from the bottom. We will understand by "difficult bottom topography" a relief in which the dimensions of obstacles in the direction of the HUV motion exceed the distance to the obstacle required for safe maneuver to overcome the obstacle, and the slope angles exceed the maximum value of the trajectory angle created in this case. We can talk about obstacles, the dimensions of which are tens and hundreds of meters, the slope angles are 45-60 degrees, and the distance to the bottom (along the normal to the bottom profile) is 5-10 meters. When forming a dynamic model of motion and a computational experiment, we will use as an example of the bottom relief bathymetric map fragment of the sea area in the Tatar Strait, the 3D image of which is shown in Fig. 1.
Figure 1. Reconstructed 3D image of a fragment of the bottom relief in the Tatar Strait.

For equidistant movement near the bottom with safe overcoming of obstacles, the rangefinder information of a 5-channel echolocation system (ELS) is used, the sonars of which with a narrow directivity pattern are located in the forward and lower sectors of the view. Distances to the bottom measured by sonar $d_i$ are distributed at some angles relative to the longitudinal axis of the apparatus as follows: $d_1$ - downward along the normal, $d_2$ - obliquely forward, $d_3$ - straight ahead, $d_4$ - obliquely forward and to the right, $d_5$ - obliquely forward and to the left. Let us denote $\gamma_{2,1}, \gamma_{3,2}$ by respectively the angles between $d_2, d_1$ and $d_3, d_2$ the sonar beams, both in the vertical plane $\gamma_{4,2}, \gamma_{5,2}$ and between the beams $d_4, d_2$ and $d_5, d_2$ in the horizontal plane. The measured distance to the bottom and the distance along the normal to the bottom surface in the vertical plane are related by the trigonometric expression: $\bar{h} = d_1 \cos (\psi - \theta_v)$, where $\theta_v$ is the value of the slope angle in the vertical plane (Fig. 2). A similar expression can be obtained for the horizontal plane.

Figure 2. HUV orientation relative to the bottom relief profile in the vertical plane.

The approximate value of the slope angle is determined using the ratio, which links measured bottom distances, trim and beams rangefinders $\gamma_{2,1}, \gamma_{3,2}$:

$$\theta_v = \psi + (\gamma_{2,1} + \gamma_{3,2}) - \arctan \left( \frac{d_2 \sin \gamma_{2,1}}{d_1 - d_2 \cos \gamma_{2,1}} \right)$$
Further, in the calculations, for the sake of concreteness, \( \gamma_{2,1} = \gamma_{3,2} = \gamma_{4,2} = \gamma_{5,2} = \pi/4 \) is taken, so that the slope angle in the vertical plane is determined by the expression:

\[
\theta_a = \psi + \pi/2 - \arctan \frac{d_1}{d_1 \sqrt{2} - d_2}.
\]

A similar expression for the horizontal plane is:

\[
\theta_m = \chi + \pi/2 - \arctan \frac{d_3}{d_3 \sqrt{2} - d_4},
\]

\[
\theta_a = \psi + \pi/2 - \arctan \frac{d_3}{d_3 \sqrt{2} - d_4},
\]

\( \theta_{gr}, \theta_{gl} \) - slope angles to the right and left relative to the direction of travel, \( \chi \) - trajectory angle in the horizontal plane.

2. Mathematical model of the dynamics of HUV

We will consider the dynamics of the patrol HUV, performing survey missions in a difficult bottom topography, using the research results obtained in [2, 3]. The spatial motion of the HUV can be represented as a set of three plane motions, the kinematic relationship of which is carried out only through the control and disturbing influences [2-5].

\[
\begin{align*}
    m_x \ddot{\chi} &= -R_x(\psi, \alpha) + P \sin \theta + T_{x_1} \cos \alpha - T_{y_1} \sin \alpha, \\
    m_y \ddot{\chi} &= R_y(\psi, \alpha, \psi') + P \cos \theta + T_{y_1} \cos \alpha + T_{x_1} \sin \alpha, \\
    J_{xy} \ddot{\psi} &= M_y \sin \psi + M_1(\alpha, \chi, \psi') + M_{x_1}, \\
    \dot{X} &= \nu \cos \theta, \quad \dot{Y} = -\nu \sin \theta, \quad \dot{\psi} = \theta = -\alpha.
\end{align*}
\]

Equations (1) use the designations adopted in [2-5], in particular: OXYZ - inertial (polygon coordinate system); \( A_{X}, A_{Y}, A_{Z} \) - vehicle-associated coordinate system; \( A_{X}, A_{Y}, A_{Z} \) - high-speed (flow) coordinate system placed in the center of mass of the vehicle and oriented by the axis \( A_{X} \) by velocity vector \( \nu \); \( m_x, m_y, m_z, I_{xx}, I_{yy}, I_{zz} \) - masses and moments of inertia of the apparatus, taking into account the added masses and moments of inertia of the liquid; \( T_{x_1}, T_{y_1}, T_{x_2}, T_{y_2}, M_{x_1}, M_{y_1}, M_{x_2}, M_{y_2} \) - the control forces and moments of the propulsion and steering complex in a connected coordinate system; \( \theta, \chi, \psi \) - angles of ascent, rotation and inclination of the trajectory; \( \phi, \psi, \theta \) - angles of heading, trim and roll of the apparatus; \( \alpha, \beta, \gamma \) - angles of attack, drift and slip; \( R_x, R_y, R_z, M_x, M_y, M_z \) - hydrodynamic forces and moments; \( M_0 = \gamma V_o h_o \) - moment of stability; \( \gamma \) - specific gravity of liquid; \( V_o \) - volumetric displacement of the apparatus; \( h_o \) - metacentric height; \( P = \gamma V_o \) - residual buoyancy of the vehicle.

3. Hydrodynamics of HUV and power characteristics of the propulsion and steering complex

For computational experiments, a spatial model of the HUV was adopted, the external view and kinematic diagram of propulsion and steering system (PSS) of which is shown in Fig. 3. The PSS provides the operation of the HUV both in an autonomous mode when performing survey and search.
operations, and in a supervisory control mode via a communication cable during dynamic positioning over an object. The use of stern propulsion devices with a drive in the vertical plane in this arrangement provides trim control over the entire range of travel speeds.

To determine the hydrodynamic characteristics of the model, we used the "virtual blowdown" software (CAD "SolidWorks"), which allows to build visualized patterns of the flow around a body in the incident flow field.

In fig. 4 shows the dependences of positional forces and moments of hydrodynamic resistance on the angles of attack and drift in the range of their variation ± 180°. To determine the damping forces and moments, the model of the vehicle rotated about the center of mass in the incident flow field at a speed of 0.1 rad/s.

4. Algorithm for routing the motion of HUV near the bottom with a bypass (inspection) of targets (objects)

Let the HUV mission include a sequential walk (inspection) of \( j \leq N \) targets (objects), the position of which is determined by coordinates with a given neighborhood radius \( \varepsilon \). It is assumed that the location of the HUV is determined using a navigation complex, which includes onboard and hydroacoustic navigation systems. With purposeful movement and detection of an obstacle in the front view sector of the ELS, according to a given criterion, its size is estimated in order to develop an appropriate control action. Depending on the size of the obstacle, it is overcome "on the move", or with the regulation of
speed and angular position relative to the obstacle. To overcome a major obstacle, it is necessary to make a maneuver with the help of the propulsion and thrusters that are part of the PSS. When the vicinity of the current target (object) is reached, dynamic positioning is performed for a specified period of time, after which the device is directed to the new target. The cycle ends when the final goal is reached. The algorithm presented in the StateFlow Simulink Matlab notation is shown in Fig. 5.

The algorithm consists of two parallel processes. The first process, implemented by the POSITIONXY function (HUVmode, PointNumber, VCMode, DepthHeight), is associated with routing motion when avoiding targets with specified coordinates and switching motion modes, (Patrolling_motion). The second process is to correct motion in the event of obstacles in the forward looking sector (Critical_correction). The correction algorithm is implemented by the MOVECORRECTION function (ForwardSonar, LeftSonar, RightSonar).

With an equidistant motion near the bottom with a relatively flat topography, a control is formed that provides stabilization of a given distance to the bottom "on the move" [2, 4]. In this case, the control action is proportional to the linear and angular misalignments at the given values of the stabilized quantities:

\[
T_{y_1} = K_{d1} (d_1 - d_{1s}) + K_{d2} (d_2 - d_{2s}) + K_{\theta v} (\theta_v - \psi), \quad |T_{y_1}| \leq T_{y_1}^{\max},
\]

where \(d_{1s}, d_{2s}\) – preset values of distances to the bottom in two directions, \(K_{d1}, K_{d2}, K_{\theta v}\) – customizable control parameters, the choice of which ensures the specified control quality, \(T_{y_1}^{\max}\) – limitation on the size of the control action.

The control algorithm when maneuvering near a large obstacle takes into account the possibility of maneuvering around or avoiding the obstacle and speed regulation depending on the position of the vehicle relative to the obstacle. To bypass the obstacle in the horizontal plane, a control action is generated:

\[
T_{z_1} = K_{d4} (d_1 - d_{4s}) + K_{d2} (d_2 - d_{2s}) + K_{\theta g} (\theta_g - \chi), \quad |T_{z_1}| \leq T_{z_1}^{\max},
\]

when going around the obstacle on the right and

\[
T_{z_1} = K_{d5} (d_5 - d_{5s}) + K_{d2} (d_2 - d_{2s}) + K_{\theta g} (\theta_g - \chi), \quad |T_{z_1}| \leq T_{z_1}^{\max},
\]

when going around the obstacle to the left.

Figure 5. Algorithm for patrolling specified targets (objects).
The distance measured by the front sonar \( d_3 \) is used to control the speed of movement when sufficiently high and steep obstacles are detected. Speed control is carried out by changing the value of the longitudinal stop:

\[
T_{s1} = T_{s1}^{\text{max}} \cdot \text{sat}\left(\frac{d_3}{d_3^{\text{max}}}\right),
\]

where \( T_{s1}^{\text{max}} \) corresponds to a given speed of motion, \( d_3^{\text{max}} \) – the limit value of the range measured by the front sonar.

When performing a maneuver to overcome an obstacle, the influence of the roll on the dynamics of transient processes, as the simulation results show, can be neglected due to the vehicle's own stability.

A computational experiment using real and model initial data makes it possible to evaluate the dynamic properties of the control system during the implementation of the main modes of movement when patrolling the survey area (result in Fig. 6). In accordance with the general provisions, the following elements were included in the computational model of the motion of the HUV:

- start from a given initial position in OXYZ coordinates with the transition to equidistant movement in height from the bottom (5m) using navigation data and data from the ELS model,
- purposeful movement with overcoming obstacles and achieving specified objects (goals) in the order of their location,
- dynamic positioning (hovering) in the vicinity of the inspected targets while maintaining the specified motion parameters (height above the bottom, speed, course, radius of maneuvering).

**Figure. 6.** Spatial position of the trajectory of motion in the patrol mode; the trajectory is periodically (~ 10 min) marked with the longitudinal axis of the HUV and the beams of the ELS; at control point # 2 it is positioned, the rest of the point passes by.
5. References

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