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Modeling and Simulation of Automatic Berthing based on Bow and Stern Thruster Assist for Unmanned Surface Vehicle

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ABSTRACT

In order to solve the technical problems of autonomous berthing of the Unmanned Surface Vehicle (USV), this research has met the requirements of maneuverability berthing under different conditions by effectively using the bow and stern thrusters, which is a technological breakthrough in actual production and life. Based on the MMG model, the maneuverability mathematical model of the USV with bow and stern thruster was established. And the motion simulation of USV maneuvering was carried out through the numerical simulation calculation. Then the berthing plan was designed based on the maneuverability analysis of the USV low-speed motion, and the simulation of automatic berthing for USV was carried out. The research results of this paper can be of certain practical significance for the USV based on the support of the bow and stern thruster in the berthing. At the same time, it also provides a certain theoretical reference for the handling of the USV automatic berthing.

1. Introduction

Unmanned Surface Vehicle is a new product that combines traditional ship technology with unmanned technology, and it mainly performs dangerous tasks. Or it can replace tasks performed manually, such as reconnaissance, search, detection, mine clearance, hydrological data survey, and execution of special operations tasks. The USV has the characteristics of unmanned autonomy, strong maneuverability, good stealth performance, and low cost. It has great application potential in military and civilian fields, and has attracted widespread attention. However, the berthing operation of the USV is one of the most complicated operations. The berthing of large ships depends on

tugboats to achieve berthing. According to statistics, 70% of berthing accidents are related to the driver's poor boatmanship in the port. In order to realize the autonomous berthing of the USV, it is of great significance to study the autonomous berthing technology of the USV. Based on the berthing simulation, the automatic berthing technology of the USV can be improved to reduce accidents when the USV is berthing at the dock, and to maintain the safety of the USV. Yang K.U. et al. (2017)^[1] described an automatic berthing system with mooring lines. It was designed to be berthed by using mooring device on the upper deck of a ship. Ablyakimov and Shirokov deals with principles and methods of development of local navigation system based on the homodyne signal transforming. It could be used for

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automatic ship berthing (Ablyakimov and Shirokov 2017)^[2]. Ship Berthing dock operation was still carried out by the operator in accordance with the traditional method of manipulation, so the ship's own professionalism determines the safety of the ship berthing, a little attention would cause accidents, so the project based on the park simulation experiment could simulate the end of the ship by the end of the docking dock, the situation. A mathematical model for simulating ship berthing or unberthing with lateral thruster was developed to improve ship maneuvering safety in port (see LiuChun-Sheng and HongBi-Guang et al. 2007)^[3]. The Artificial Neural Network (ANN) model was an effective theory of automatic ship berthing, which could simulate human brain's action in the ship berthing stage through learning (Ahmed Yaseen Adnan et al.2014^[4]; Im Nam-Kyun et al.2018^[5]; Tran Van Luong et al.2012^[6]; Ahmed Yaseen Adnan et al.2012^[7]). Aiming at the track planning of unmanned boat berthing, Zhang discussed the improved artificial potential field method based on the analysis of berthing constraint, and studied the autonomous track planning technology of berthing(Zhang Weibin.2017^[8]). The increase of the ship's speed will lead to the reduction of the thrust of the bow thruster (see Yan. 2008^[9]; Bai Jun. 2010^[10]). Im and Nguyen^[11] proposed a new artificial neural network controller using a head-up coordinate system containing the relative position of the ship and the distance from the berth. Without retraining the artificial neural network structure, automatically control ships to enter berths in different ports. Hu^[12] studied the unsteady force characteristics of the rear propeller of the small waterplane area catamaran and compared the accuracy of the numerical calculation method with the experimental results. Taimuri et al.^[13,14] present a 6-DoF kinematic model to quickly estimate the maneuvering trajectory and hydrodynamic actions in deep and shallow waters. It can be used for the prediction of maneuvering trajectories of existing or new-build vessels and for estimating the evasive velocity. In 2019, Li et al.^[15] proposed a layered artificial potential field trajectory planning method based on multi-constraint analysis of berths, environmental obstacles, and hull dynamics to realize the autonomous trajectory planning of USV. In (Wu et al.,2021)^[16], an algorithm of berthing and maneuvering was designed for a catamaran USV.

In this paper, the MMG mathematical model is applied to establish the USV maneuvering motion mathematical model with bow and stern thrusters. In section 2, the mathematical model for the Automatic Berthing USV is established. In section 3, the rudder force and its torque are calculated. In section 4, the thruster thrust and torque are calculated. The berthing path is designed for USV in

section 5. The simulation and analysis for USV Automatic Berthing were executed in section 6. Finally, the USV's autonomous berthing simulation is summarized.

2. Establishing the Mathematical Model for the Automatic Berthing USV

The equation of USV in motion coordinate system:

$$\begin{cases} m(\dot{\mu} - vr) = X \\ m(\dot{v} + \mu r) = Y \\ I_{zz}\dot{r} = N \end{cases} \quad (1)$$

Among them, m represents the quality of the USV, μ is the longitudinal velocity, v is the transverse velocity, r is the angular velocity, Y is the total transverse moment, X is the total longitudinal moment, I_{zz} is the moment of inertia about Z axis. The right side of the above formula is the force of the hull, which is represented by the following expression:

$$\begin{cases} X = X_H + X_P + X_R \\ Y = Y_H + Y_P + Y_R + Y_{BT} + Y_{ST} \\ N = N_H + N_P + N_R + N_{BT} + N_{ST} \end{cases} \quad (2)$$

Among them, subscripts H represents the hull, P represents the propeller, R represents the rudder, BT represents the bow thrust, ST represents the stern thrust.

During the operation of the USV, the maneuvering of the USV, the provision of the main control force and the resistance to overcome the water flow are all provided by the thrust generated by the propeller, which is an essential force to be studied. We use the MMG model to derive the expression of the paddle force and its torque as:

$$\begin{cases} X_P' = (1 - t_p)\rho n^2 D^4_p K_T(J_p) / \frac{1}{2} L D U^2 \\ Y_P' = 0 \\ N_P' = 0 \end{cases} \quad (3)$$

Among them, X_P' is the longitudinal moment provided by the propeller, t_p is thrust reduction factor, ρ is the density of the fluid, n is main engine speed; D_p is propeller diameter, $K_T(J_p)$ is Propeller thrust coefficient; $K_Q(J_p)$ is Propeller torque factor, L is the length of the USV, D is the draft of the USV, U is the speed of the USV, Y_P' is the lateral moment provided by the propeller, N_P' is the torque around the center of the USV under the action of the propeller.

3. Calculation of the Rudder Force and Torque

The rudder is generally installed at the tail of the USV to increase the control of the USV. The expression of the USV's rudder force and its torque is:

$$\begin{cases} X_R = -(1 - t_R)F_N \sin \delta \\ Y_R = -(1 + a_H)F_N \cos \delta \\ N_R = -(1 + a_H)X_H F_N \cos \delta \end{cases} \quad (4)$$

Among them, X_R is the distance from the point of action of the rudder force to the center of gravity, t_R is rudder angle correction force coefficient, F_N is rudder positive pressure, δ is rudder angle, a_H is hull force correction factor; X_H is transverse force to gravity distance.

The expression of the rudder positive pressure is:

$$F_N = \frac{1}{2} \rho \frac{6.13\lambda}{\lambda + 2.25} A_d U_R^2 \sin \alpha_R \quad (5)$$

Among them, F_N is rudder positive pressure, A_d is rudder leaf area; U_R is effective flow rate into the rudder; α_R is effective rudder angle into the rudder.

4. Calculation of Thruster Thrust and Torque

The hydrodynamic force of the thruster is mainly affected by the following parameters: (1) USV speed; (2) USV draught; (3) Ratio of draft to water depth; (4) The projected area of the blade; (5) The ratio of the length of the blade to the diameter of the paddle; (6) The shape of the end of the blade; (7) The aspect ratio of the paddle.

4.1 Thrust Calculation without Speed

When there is no speed, the thrust of the thruster is equivalent to the thrust generated by the semi-infinite flow, expressed by the following formula:

$$T = \rho F_j V_j^2 \quad (6)$$

Among them, T is the thrust of the propeller, ρ is the density of the fluid, F_j is channel cross-sectional area; V_j is jet velocity.

4.2 Thrust Calculation at Speed

When the USV has a forward speed, there will be mutual interference between the speed of the USV and the jet velocity of the side propeller. This action will produce an adsorption force ΔT , so the actual thrust is:

$$Y_{BT} = T - \Delta T \quad (7)$$

According to the experimental results obtained from the bubble experiment, it is concluded that when the USV speed and jet velocity ratio are not too large, ΔT can be ignored, If $V_s/V_j < 0.3$, Thrust of the ankle thruster T and Torque N can be estimated by the following formula:

$$\begin{cases} Y_{BT} = T \left[1 - 1.4 \frac{V_s}{V_j} \left(\frac{V_s}{V_j} + 1 \right)^2 \right] \\ N_{BT} = T \left[x_p - 1.4 \frac{V_s}{V_j} \left(\frac{V_s}{V_j} + 1 \right)^2 x_p + \frac{V_s}{V_j} \cdot \frac{B'}{2} \right] \end{cases} \quad (8)$$

Among them, T is mooring thrust; V_s is USV speed; V_j is bow side thruster jet velocity; x_p is distance between the thruster channel and the origin of the USV's coordinates; B' is USV width at the axis of the channel.

$$\begin{cases} Y_{ST} = T_s \left[1 - 1.4 \frac{V_s}{V_{sj}} \left(\frac{V_s}{V_{sj}} + 1 \right)^2 \right] \\ N_{ST} = T_s \left[x_{sp} - 1.4 \frac{V_s}{V_{sj}} \left(\frac{V_s}{V_{sj}} + 1 \right)^2 x_{sp} + \frac{V_s}{V_{sj}} \cdot \frac{B_s'}{2} \right] \end{cases} \quad (9)$$

Among them, T_s is mooring thrust; V_s is USV speed; V_{sj} is stern side thruster jet velocity; x_{sp} is distance between the thruster channel and the origin of the USV's coordinates; B_s' is USV width at the axis of the channel.

5. Berthing Path and Simulation Design of Automatic Berthing for USV

In simulating the USV berthing simulation assisted by the head and tail thrusters through simulation software, it is necessary to first make a berthing plan and prepare for the berthing pier:

1. Understand the port's topography, water depth, width, speed limit in the port, port heading area, no anchor area, communication facilities, berth size (generally 1.15 to 1.2 times the length of the captain) and whether there are obstacles before and after the berth will affect the berthing condition.
2. The expected timing, flow rate, flow direction and wind direction of the USV at the dockside when berthing, and the influence of wind on the maneuvering when the USV is berthing. When the still water flows, the main consideration is the role of the wind. In the tidal port, it is necessary to grasp the timing of the flow and the timing of the tide.
3. Determine the berthing plan and prepare for the anchor at any time.

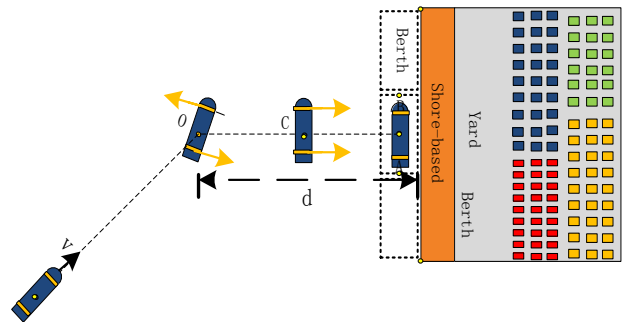


Figure 1. Berthing path design for USV

As shown in Figure 1, in order to design the berthing path for USV, firstly, the position coordinates of the USV's starting point O need to be determined. Before the USV enters the breakwater and enters the harbor basin, it needs to stop. At this time, the stop point is the initial Click O. After that, the location of the vacant berth needs to be determined, the center point E of the vacant berth suitable for this USV to be docked is determined, and the coordinates are determined, and the positions of the end points A and B are determined according to the length of the berth, and their coordinates. Then make a vertical line to the longitudinal axis of the berth to be berthed, and draw a transverse line perpendicular to the longitudinal axis of the berth. On this line, the USV needs to move horizontally, and the tugboat is used to assist the lateral movement of the USV to complete the berth. The starting point is point E, the end point is point C, and the distance of the line segment EC is d. According to the corresponding port regulations, the length of d is not less than 2.5 times the width of the USV. Because the windward heading of the USV needs to be considered during the berthing process, the USV needs to be considered. Therefore, it is necessary to carefully consider the distance of d and carefully determine the coordinates of C. Then connect the center point of the USV and the starting point O to point C to form the berthing path of the broken line OCE. After completing the global route planning for USV berthing, implement the specific USV berthing.

6. Simulation and Analysis for USV Automatic Berthing

First, on the XOY coordinate system, four destination points can be selected from the USV model as the origin to simulate the USV's berthing. These four waypoints can form a route to completely represent the entire berthing process, as shown in the following figure:



Figure 2. Right berth route plan

Because the research in this paper is based on the side thrusting aid, the side push selects the side thrust and the side thrust pushes; the towing method selects the translational towing mode; then selects the berth route plan table 0, 1, 2, 3. These four waypoint numbers define the USV's heading and speed for each waypoint, as shown in the following table:

After this, according to the above chart generation can generate a berthing route planning route plan, the implementation of our planned route, the USV model can begin to simulate the vessel from the beginning of the port to the end of the berthing with the support of the side of the berthing plan, the role of the bow and stern side of each waypoint is as follows:

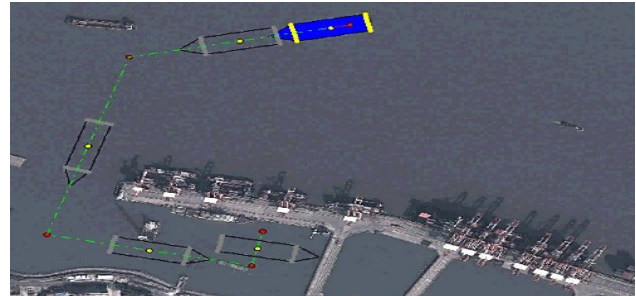


Figure 3. Berthing plan of USV aided by bow and stern thruster at point No. 0

Table 1. Each waypoint definition table on the route

Plan number	Towing type	Starting pointX	Starting pointY	End X	End Y	Ship heading	Speed
0	Translation	0	0	-390.92	-86.71	0Along the route	3
1	Translation	-390.92	-86.71	-536.35	-563.78	0Along the route	2
2	Translation	-536.35	-563.78	-174.56	-647.13	0Along the route	1
3	Translation	-174.56	-647.13	-155.05	-554.91	2Vertical route	0.8

The above figure is the case where the USV has just begun berthing at Route No. 0.

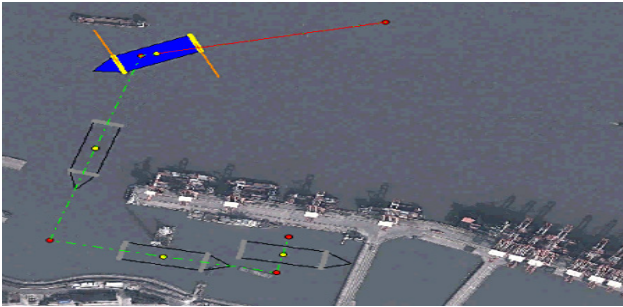


Figure 4. USV berthing diagram assisted by the stern side thruster of No. 1th waypoint

The above figure shows that when the USV sails on the route to the 1st waypoint, the thruster assists the USV to assist the USV in steering, and the side thruster and the side thruster respectively generate side thrust, thus assisting The USV completes the steering in the berth.



Figure 5. USV anchorage map assisted by No. 2 waypoint thruster

The above picture shows that the USV sailed on the following route. When it sailed to the 2nd waypoint, the thruster once again assisted the side push, generating the thrust to make the USV complete the steering and enter the set route. Continue to berth.

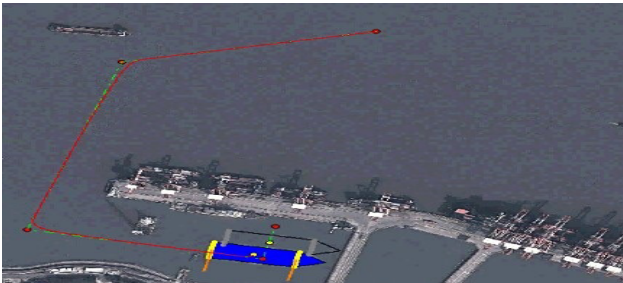


Figure 6. USV anchorage map assisted by No. 3 waypoint thruster

The above figure shows that when the USV is routed to the No. 3 waypoint, the USV is required to carry out the work of the port. The thruster once again generates the

measured thrust to allow the USV to reach the designated berth on the normal flight route, completing the entire berthing process.

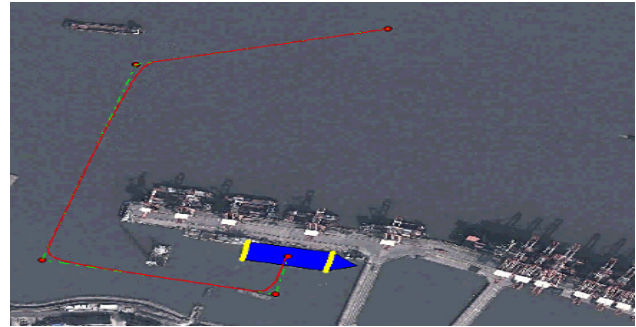


Figure 7. USV anchorage map assisted by No. 4 waypoint thruster

The above picture shows that the berthing plan for the entire route we set was completed when the USV reached the 4th waypoint. Thus, we have completed the entire berthing process and we can get the berthing track of the entire berthing plan, as shown below:

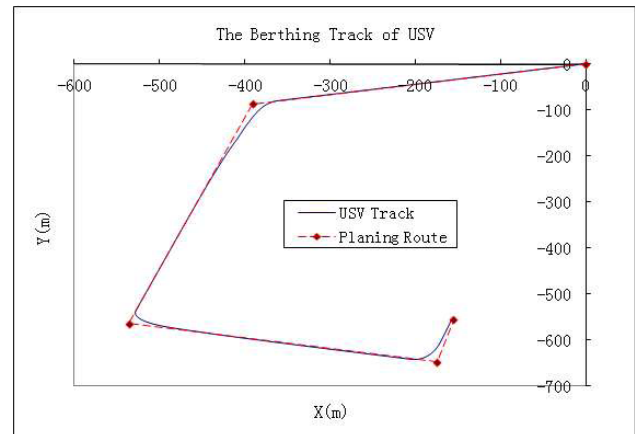


Figure 8. The berthing track of USV

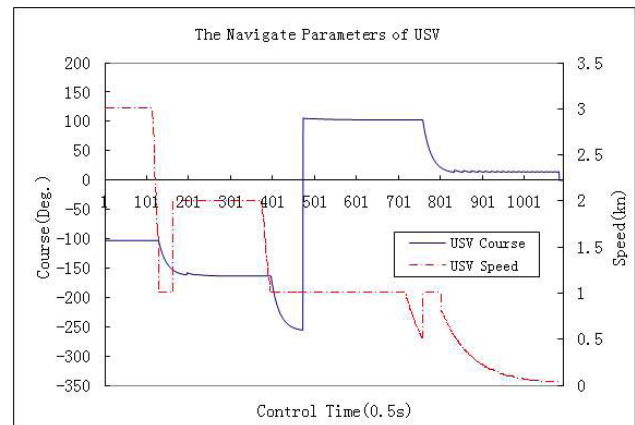


Figure 9. The USV berthing navigation parameter

As shown in Figure 8, the USV's trajectory is compared with the planned berthing path. When the USV berths simulation, it can track the designated berth planning route. Only when the route is switched, there is some tracking error. Figure 9 depicts the changes in the speed and heading of the USV over time when the USV is automatically berthed. It can be seen from this figure that when the USV approaches the dock, its heading tends to the direction of the dock. His speed approached zero, and he finally docked safely at the designated dock location. Through the USV berthing simulation program and berthing planning route designed in this paper, the autonomous berthing simulation of the USV can be realized.

7. Conclusions

In this paper, a three-degree-of-freedom maneuvering mathematical model based on the head-tail side-push aided USV was established by using the MMG model. Firstly, the forces and moments acting on the USV's hull were calculated. By calculating the hydrodynamic derivatives and inertia moments, a more complete and reasonable three-degree-of-freedom USV maneuvering model is established. After the completion of the mathematical model, the thrust of the lateral thruster is calculated. Then the USV berthing process assisted by thrusters was planned. And the computer software is designed to realize the simulation of the USV berthing based on the head-tail pushing assistance. Finally, by analyzing the simulation results, this paper provides a reference scheme for USV maneuvering with the help of the head and tail thrusters. There is the practical significance for the safety of USV berthing.

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