Research on a course control strategy for unmanned surface vessel

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Abstract: With the development of intelligent control and modern communication technology, Unmanned Surface Vessel (USV) will soon become another important unmanned platform after drones and unmanned vehicles. Unmanned vessel are easily disturbed by wind, waves and currents during navigation. Solving the problem of unmanned vessel's course keeping control during navigation has become one of the key technologies in the research of unmanned vessel. Aiming at the course control problem of the unmanned vessel in the course of navigation, this paper firstly carried out mathematical modeling and data analysis on the dynamic model of the experimental unmanned vessel, carried out related design simulations and experiments through the constructed model, and propose an optimal control strategy based on PID controller. On this basis, the accuracy and effectiveness of the control strategy proposed in this paper are verified through a simulation platform, which can ensure the course stability of the unmanned vessel during the navigation process. Key technologies such as UAV obstacle avoidance and coordination provide a theoretical basis.

1. Introduction

With the rapid development of modern artificial intelligence and intelligent manufacturing, the intelligent transportation system of the trinity of land, sea and air has become the future development trend [1]. At present, the development of unmanned aircraft and unmanned vehicles has become increasingly mature, but the development of unmanned surface vessel is still in the preliminary exploration stage, and their key technologies such as course control, speed control, obstacle avoidance, and multi-unmanned vessel cooperation are attracting the key attention of many experts, scholars and university teachers and students. Unlike unmanned aircraft and unmanned vehicles, unmanned vessel are greatly influenced by wind, waves, currents and other environmental disturbances in water navigation, and have very complex nonlinear characteristics for course control systems, so it is necessary to study the course control of unmanned vessel [2]. The goal of unmanned vessel course control is to make the unmanned vessel navigate according to the set course, and the course control mainly includes two aspects: course maintenance is to make the unmanned vessel recover to the set course with the least control force and the shortest time when it is disturbed by the outside world, and course change is to make the unmanned vessel track to the new set course quickly and accurately with the least amount of overshoot [3].

With the continuous development of modern control theory and computer technology, scholars at home and abroad have applied some new control algorithms to unmanned vessel course control, such as feedback linearization [4], QFT control [5], generalized predictive control [6], LQR control [7], and LQG
methods [8]. These control theories and algorithms have achieved certain results in the research of course control of unmanned surface vessel, but some of these methods have high requirements on the control object model, and some of them make it difficult to guarantee the control effect because they are limited by the nonlinearity and uncertainty of the unmanned vessel motion system, and even affect the stability of the system under certain operating conditions. Regarding the unmanned vessel course control, the most widely used is still the PID controller proposed by Minorsky [9], and the PID controller-based course control algorithm has the advantage over the above-mentioned control methods and other modern intelligent control techniques, because other control techniques may control better in a certain kind of water and environment, but the effect in complex water and complex environment still needs to be improved.

2. Unmanned vessel dynamics model
The motion control of the unmanned vessel is relatively complex, usually with six degrees of freedom, namely, forward, transverse motion, vertical swing, longitudinal swing and bow swing. In this paper, the inertial coordinate system is shown in figure 1, O0-X0Y0Z0 is the inertial coordinate system fixed on the earth's surface (also called geodetic coordinate system), which stipulates that X0 points to due north, Y0 points to due east, and Z0 points to the center of the earth (also called north-east geodetic coordinate system).

![Figure 1 Inertial coordinate systems](image)

O-xyz is a north-east geodesic coordinate system whose origin is located at the symmetry point O of the hull in the unmanned vessel, with the x-axis pointing to the bow, the y-axis pointing to the starboard side, and the z-axis pointing to the keel, and each axial unit vector is recorded as $i, j, k$. The motion of the unmanned vessel is analyzed from the viewpoint of rigid body motion, which can be regarded as two components: translational motion with the O point and winding motion around the O point. As shown in figure 2, the six components on O-xyz are $u, v, w, p, q, r$. $u$ represents surge velocity, $v$ represents sway velocity, $w$ represents heave velocity, $p$ represents the rolling rate, and $q$ represents the pitching rate, and $r$ represents yaw rate. It can be obtained as follows:

$$
V_0 = u\hat{i} + v\hat{j} + w\hat{k}
$$

$$
\Omega = p\hat{i} + q\hat{j} + r\hat{k}
$$

In equation (1), the absolute velocity vector at point O and the angular velocity of rotation at point O are represented. For the majority of ship motions, the forward motion dominates, accompanied by oscillatory motions in the direction of other degrees of freedom.

![Figure 2 Unmanned vessel water movement three-dimensional map](image)
This paper focuses on the motion control of an unmanned vessel on the water surface. For most cases of ship motion control, the main controlled motion parameters are surge velocity $u$, sway velocity $v$, and yaw rate $r$. The unmanned vessel is considered to be in plane motion. The heave velocity $w$, rolling rate $p$, pitching rate $q$ can be neglected. That is, $w=p=q=0$, so the kinematic model of the unmanned vessel is simplified to a kinematic problem with three degrees of freedom. As shown in figure 3, $\Psi$ is the course angle, $\delta$ is the rudder angle, $\beta$ is the drift angle, and $V$ is the motion speed of the unmanned vessel.

Because the hull mass of the unmanned vessel is symmetrically distributed in the xz plane, the rotational inertia $I_{xy}=I_{yz}=0$, and the y-axis coordinate of the center of gravity $G$, $y_G=0$, so the equation of motion of the unmanned vessel is simplified to the following form:

$$m(\ddot{u} - rv - x_Gr^2) = X$$
$$m(\ddot{v} + ru - x_G\dot{r}) = Y$$
$$I_{zz}\ddot{r} + mx_G(\dot{v} + ru) = N$$

In equation (2), $m$ is the mass of the unmanned vessel, $I_{zz}$ is the rotational inertia around the z-axis, and $X$, $Y$, $N$ are the hydrodynamic forces and moments acting on the unmanned vessel in the $x$, $y$, $z$ directions, respectively.

3. Design of course controller

3.1. Unmanned vessel course control principle

The most important part of the unmanned vessel course control is the control of the rudder of the unmanned vessel. Figure 4 is the schematic diagram of the unmanned vessel course control system, the system is a dual feedback closed-loop stabilization system, the external closed-loop is the course comparison link, through the actual course and the given course to compare the amount of course deviation, and then feedback to the course controller part, through the course controller algorithm to calculate the amount of rudder angle offset, and then passed to the servo mechanism to control the rudder angle offset. The internal closed loop is the rudder angle comparison link, which compares the actual rudder angle value with the given rudder angle value, and controls the servo mechanism through the rudder angle feedback device to continue working until the actual rudder angle value has no deviation from the given rudder angle value, at which time the deviation amount between the external actual course and the given course is zero, and then the unmanned vessel course control system is in the equilibrium state.

![Figure 3 Unmanned vessel horizontal plane movement schematic](image)

![Figure 4 Unmanned vessel course control system schematic](image)
3.2. **PID course control algorithm**

In the course of unmanned vessel's course control, its reliability and stability are of the utmost importance. Because of the simple structure, high reliability and good effect in complex environment, PID control algorithm is widely used in various systems and can play an extremely stable control effect in the course control system of unmanned vessel. The block diagram of a typical PID control algorithm is shown in figure 5:

![Block diagram of PID control algorithm](image)

As shown in figure 5, the deviation $e(t) = r(t) - c(t)$ is calculated according to the given value $r(t)$ and the output value $y(t)$, and then the deviation $e(t)$ is output by proportional, integral and differential operations to control the controlled object, and the PID control output is:

$$u(t) = K_p e(t) + \frac{1}{T_i} \int e(t) dt + T_d \frac{de(t)}{dt}$$

(3)

In equation (3), $K_p$ is the proportional coefficient, $e(t)$ is the difference between the given course and the actual course angle, $T_i$ is the integration time constant, $T_d$ is the differential time constant. $K_p$, $T_i$, $T_d$ adjust the parameters according to the actual course control situation. Each link of the PID controller works as follows.

1. **Proportional (P) link**: Proportional link will control the deviation of the system $e(t)$ in proportion to the feedback, when the deviation of the controller to play a control role.
2. **Integral (I) link**: The integral link is mainly used to eliminate static errors and improve the control system's non-differential degree. The strength of the effect is mainly related to the integration time constant $T_i$, which is negatively correlated with the integration time constant.
3. **Differential (D) link**: The differential link is mainly used to speed up the response of the control system, reflect the trend of the system deviation signal as well as reduce the system regulation time [9].

The schematic diagram of the PID course control algorithm applied to an unmanned vessel is shown in figure 6:

![PID course control algorithm schematic](image)

4. **Simulation and verification of unmanned vessel course control algorithm**

This section mainly studies the simulation verification of the PID course control algorithm for the unmanned vessel course control effect. Based on the mathematical motion model of the unmanned vessel.
vessel established in Section 2, the simulink simulation platform in MATLAB is used for the experimental verification of the unmanned vessel course control simulation.

![Unmanned vessel course control simulation diagram](image)

Figure 7 Unmanned vessel course control simulation diagram

In figure 7, the initial value of the unmanned vessel speed and the coordinate system and initial course are pre-processed first, then a perturbation with a unit step signal is applied, and the rudder angle value is output by the controller and the rudder angle deflection is controlled by the servo to complete the unmanned vessel course control.

The rudder angle change curve and course change curve when the unmanned vessel is disturbed at a higher speed of 20 knots and a given course of 20 are shown in figure 8:

![Simulation results of rudder angle and course change curve at 20°](image)

Figure 8 Simulation results of rudder angle and course change curve at 20°

The rudder angle change curve and course change curve of the unmanned vessel with a speed of 20 knots and a given course of 30 subject to perturbation are shown in figure 9:

![Simulation results of rudder angle and course change curve at 30°](image)

Figure 9 Simulation results of rudder angle and course change curve at 30°

According to Figure 8 and Figure 9, when the given course is 20°, the rudder angle deviation is small, and the overshoot and steady-state time are smaller than 300. But in both cases, it can achieve a good course control effect, and can meet the requirements of stability, accuracy and speed.
5. Summary
This paper firstly briefly describes the unmanned vessel dynamics model, establishes a three-degree-of-freedom unmanned vessel dynamics model for practical applications, and proposes the kinematic equations; secondly, briefly analyzes the unmanned vessel course control principle, and on this basis, in order to ensure the stability of the course controller, introduces the PID course control algorithm into the unmanned vessel course control, and designs an unmanned vessel course control with good results. Finally, the simulation is verified on MATLAB platform, and the results show that the method can make the unmanned vessel course control more effective and basically achieve the characteristics of stability, accuracy and speed in the unmanned vessel course control process.

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