Design of the Surface USV Heading Controller Based on the Predictive Function Control Principle

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Abstract: In view of the controlling issues such as the steering restraints on the water and the turbulence by wind, wave, current and else in the midst of voyage, this paper designed a type of surface USV heading controller on the basis of predictive function control principle. The controller adopted the thought of prediction prior to control. With full consideration of above mentioned restraints and disturbance that affect the heading control, when the optimum control quantity was solved online, it fulfilled timely compensation on the turbulence. After that, simulation experiment was carried on upon the heading controller that was steered by predictive function; moreover, in comparison with the heading controller that was steered by traditional PID, it validated the effectiveness of the newly designed controller. In addition, it provided support for subsequent design of indirect flight path algorithm.

1. Introduction
The surface USV is a significant component in construction of marine intelligent system. As the USV intelligent control technology develops, USV has seen an increasingly wide application in the maritime field [1]. It plays an essential role in promoting maritime intelligent management, maritime search-and-rescue emergency success rate and other aspects.

In virtue of the thought of prediction prior to control, the Model Predictive Control (also known as MPC) algorithm endows the steered object with more sensitively controlling response. Therefore, it can adjust the control action at a faster rate in accordance with the external interference. Simultaneously, the algorithm controls the online optimization process that arises from its inner optimum controller, thus further improving the processing capacity [2-3] that control system handles the uncertainty of the steered object. The predictive function control is known as the third generation MPC. On the basic of retaining the fundamental characteristics of MPC, it added the procedure of structuring the control input, and decomposed the control quantity into linear combination of primary functions. Consequently, it improved the regularity of control input and decreased the computation load. In terms of above features of the MPC, the model predictive control algorithm is extremely valuable in the USV heading control field. The surface USV itself is bound by steering restraints. On the voyage, it is still subject to the wind, wave, current and other turbulence. To solve the above problem, this chapter used the predictive function control algorithm to design the USV heading controller. It realized effective heading control and supported the design of indirect flight path control algorithm.

This chapter firstly introduced the design principle of the USV heading controller in the light of classic PID. Then guided by the algorithm principle of the predictive function control in the model predictive control theory, it combined with the requirements of USV heading control to design a type of USV heading controller on the basis of predictive function control algorithm. Furthermore, simulation experiment was used to validate the algorithm. At last, it made a conclusion on the contents of this
2. Heading Controller Based Upon the Classic PID Algorithm

The classic PID controlling algorithm possesses simple design structure. It has been widely applied in actual projects. In Fig. 1, it showed the USV heading control system based upon classic PID algorithm. The USV heading control system is a typical negative feedback system. Its input signal is set as the target heading angle $\psi_d$ of USV, and its output signal is set as the actual heading angle $\psi$ of USV. Accordingly the input signal of PID heading controller is set as the deviation $e(t)$ between the objective heading angle $\psi_d$ of USV and the actual heading angle $\psi$ of USV. Its output signal is set as the control quantity $\delta(t)$ of the USV steering angle.

As shown in Fig. 1, the USV heading controller based upon classic PID algorithm consists of three segments: proportion, integral and differential. The correlation of its output signal and input signal can be expressed by Formula (1).

$$\delta(t) = K_p \left( e(t) + \frac{1}{T_i} \int_0^t e(t)dt + T_d \frac{de(t)}{dt} \right)$$  \hspace{1cm} (1)

In it, $e(t)$ represents the deviation value between the objective heading angle $\psi_d$ and the actual heading angle $\psi$ of surface USV. That is, $e(t) = \psi_d(t) - \psi(t)$. $K_p$ refers to the proportional coefficient, $T_i$ refers to the integral time constant, and $T_d$ represents the differential time constant.

In the midst of controller design, normally it sets $K_i = \frac{K_p}{T_i}$ and $K_d = K_p \times T_d$ for convenience in parameter analysis and adjustment. The formula (2) was further rewritten as:

$$\delta(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}$$  \hspace{1cm} (2)

In it, $K_p$ represents the proportional coefficient, $K_i$ represents the integral coefficient and $K_d$ refers to the differential coefficient.

3. Heading Controller Based Upon the Predictive Function Control Theory

The overall flow chart of PFC-based surface USV heading control system was shown in Fig. 2. In this figure, the input signal of heading control system was expressed by the objective heading angle $\psi_d$ of USV; the output signal of heading control system was expressed by the actual heading angle $\psi$ of USV. As a result, the input signal of heading controller based upon predictive function control was the objective heading angle $\psi_d$ and the actual heading angle $\psi$ of USV. And its output signal equals the control quantity $\delta$ of the USV input steering angle. The controlling process of predictive function controller in the surface USV heading control system mainly comprises following steps:

(1). In accordance with the control quantity of current steering angle, the USV prediction model calculates the predictive output value of heading angle in time domain.
(2). According to the deviation of present actual heading angle output value from the predictive output value, it rectifies the predictive output value within prediction horizon.

(3). Based upon the optimized performance index function and present objective heading direction of USV, the optimizing controller calculates the optimal controlling sequence of the USV steering-angle control quantity within the control horizon. Additionally, the calculated optimal controlling sequence is used to determine the steering-angle controlling signal that is imposed on the USV at the present moment.

(4). Rolling optimization strategy was used on above mentioned computation process continually (shown in Fig. 2); repeat the procedure (1) – (3).

In above controlling process, the design of this heading controller mainly involves the determination of USV predictive model and optimized performance index, the formulation of feedback rectifying strategy as well as the selection of predictive horizon and control horizon parameters. Here it will concretely introduce the design process of the PFC-based USV heading controller from these aspects.

3.1. Predictive Model

The predictive model of USV heading control system refers to the model that can accurately depict the correlation of input signal and output signal in heading control system. In the research of USV heading control, Nomoto equation was used as the predictive model in consideration of its capability to describe the operational characteristics of USV. The Nomoto function was expressed as follows:

\[ T\dot{\psi} + \psi = K\delta \]  

(3)

In this function, \(K\) represents the turning index of USV. \(T\) represents the turning lag index of USV. \(\delta\) refers to the steering angle of USV; and \(\psi\) refers to the heading angle of USV.

Set the sampling time as \(T_s\); then carry on discrete operation on formula (4) to acquire the difference equation of USV predictive model as follows:

\[ \psi(k) = e^{-\frac{T_s}{T}}\psi(k-1) + K\left(1 - e^{-\frac{T_s}{T}}\right)\delta(k-1) \]

(4)

In formula (3), the turning index \(K\) of USV and the turning lag index of USV \(T\) can be acquired by \(10^5\) Z-shaped operational experiment on the existing trial vessel. The basic parameters of the trial vessel in this paper was shown as follows.

| Tab. 1 Major parameters of USV
| Primary Parameter | Length of Vessel/m | Length between Vertical Lines/m | Draught Depth/m | Mould Depth/m | Full Load Displacement/T | Highest Speed/kn | Cruise Speed/kn |
|-------------------|--------------------|---------------------------------|----------------|--------------|----------------------------|-----------------|--------------|
| Value             | 8.075              | 8                               | 0.6            | 1.15         | 3.2                        | 12              | 6            |
The $10^\circ$ $Z$-shaped experiment was carried out on the trial vessel on calm lake surface. The acquired variation curve that reflected the relationship between the heading angle and the steering angle of trial vessel was shown in Fig. 3. In light of the computing method mentioned in reference [4], the USV test data was fitted to obtain the parameter value $K$ and $T$ of the trial vessel as: $K = 0.49$, $T = 1.94$.

\[ T\dot{\psi} + \dot{\psi} = K(\delta + f_a) \]  

(5)

3.2. Feedback Correction

The feedback correction segment in the PFC-based USV heading controller was mainly implemented by rectifying the predictive heading output value in the prediction horizon that was provided by USV predictive model. It aimed to adjust the predictive value to approach the actual output value. Here it used the deviation between the predictive output steering angle $\psi_m(k)$ of given USV prediction model and the systematic actual output steering angle $\psi(k)$ at the moment to rectify the predictive output heading angle $\hat{\psi}(k+i)$ in future systematic prediction horizon. The error equation is:

\[ e(k + i) = \psi(k) - \psi_m(k) \]  

(6)

So after rectification, the output heading angle $\hat{\psi}(k+i)$ of USV prediction model in future systematic predictive horizon is expressed as:

\[ \hat{\psi}(k + i) = \psi_m(k + i) + e(k + i) \]  

(7)

3.3. Rolling Optimization

By means of rolling optimization, the PFC-based heading controller solved to acquire the optimal
steering-angle control input quantity at every corresponding moment. The acquired standard of this steering-angle control quantity reflected the preset course tracking effect of controller. On the other hand, taking into account of the maximum heading tracking, the selection of steering-angle control quantity also considered whether the steering-angle variation accord with the actual USV peering situations [5].

Consequently, the standard function was built as shown in formula (8) to evaluate the weighed mean value of the course tracking deviation square value in predictive horizon and the square value of variation increment in steering-angle control quantity within controlling horizon. And it minimized the standard function $J$ to obtain the optimized USV steering-angle input control quantity. Otherwise, the weighed factors in standard function were adjusted to reflect the significance of heading deviation and steering-angle increment in the process of solving the optimized steering-angle control quantity in controlling horizon. Normally, under the conditions of USV steering-angle restraints, the heading control effect is more significant. Thereupon, in formula (8), the weighed factor of heading deviation $a_i$ was supposed to be larger than that of steering-angle control quantity deviation $b_i$.

$$
J = \frac{1}{2} \left\{ \sum_{i=1}^{H_p} a_i \left[ \psi(k+i) - \psi_r(k+i) \right]^2 
+ \sum_{i=1}^{H_c} b_i \left[ \delta(k+i-1) - \delta(k+i-2) \right]^2 \right\}
$$

In the equation, $\psi$ represents the actual output heading angle of heading controller; $\psi_r$ represents the reference heading angle of USV; $H_p$ refers to the predictive horizon of prediction function control; and $H_c$ refers to the control horizon of prediction function control. In the meantime, $H_c \leq H_p$. $a_i$ stands for the weighing factor of heading deviation, $b_i$ stands for the weighting factor of steering-angle control increment.

Additionally, in consideration of the controlling characteristics of USV itself, when the model predictive heading controller outputs the USV steering-angle control quantity, it should take into account of the steering-angle constraint. This paper used the USV model steering-angle constraint as:

$$
-35^\circ \leq \delta \leq 35^\circ
$$

Therefore, the issue of acquiring the optimum steering-angle control quantity in rolling optimization at the moment $k$ could be converted as the partially optimal control issue which was shown in formula (10). It regarded the first control value in acquired optimal control sequence that was obtained in formula (10) at the moment $k$ as the optimum steering-angle control quantity at the moment of $k$; then it was acted on the USV heading control system, so as to fulfill the USV heading control [6].

$$
\min J = \frac{1}{2} \left\{ \sum_{i=1}^{H_p} a_i \left[ \psi(k+i) - \psi_r(k+i) \right]^2 
+ \sum_{i=1}^{H_c} b_i \left[ \delta(k+i-1) - \delta(k+i-2) \right]^2 \right\}
$$

s.t. $\delta_{\text{max}} \leq \delta_{\text{min}}$

4. Simulation Verification and Analysis

On the basis of the USV introduced in Tab. 1 of this chapter, the system simulation was developed on the designed heading control system under the matlab simulated environment to validate the availability of this controller. The system simulation mainly covered two aspects: heading maintenance and course tracking. The specific parameters were set as below:

The initial parameters of USV were set as: speed $v = 1\text{m/s}$, heading angle $\psi = 0^\circ$.

The parameters of PID heading controller were set as: $K_p = 0.5$, $K_i = 0.00005$, $K_d = 0.9$.

The parameters of PFC heading controller were set as: prediction horizon $H_p = 10$; control horizon $H_c = 2$. The weighing factors of heading deviation in objective function $J$ were: $a_i = 1, i = 1, 2, \cdots H_p$. The weighing factors of steering-angle control increment were: $b_i = 0.1, i = 1, 2, \cdots H_c$ [7].
4.1. Heading Maintenance Effect

Under ideal situation of no disturbance, it carried out simulation experiment on the heading maintenance effect of both USV heading controllers. A constant value was input into the objective heading angle $\psi_d = 10^\circ$. The acquired heading control effect was shown in Fig. 4. The variation of steering-angle control quantity was shown in Fig. 5.

Observed from Fig. 4 and Fig. 5 the simulation results under ideal situation of no disturbance, both the PFC-based heading controller and the PID-based heading controller could achieve non-overshoot given objective heading angle. Though the response rate of PFC-based heading controller was faster than that of PID-based heading controller, the former possessed relatively larger variation in steering-angle control.

Amid simulation on heading control with external disturbance, the wind and wave disturbance is substituted by the function as the white noise value multiplies the second order wave value [8]. In disturbance signals, the mean value of white noise signals is 2; the power spectral density is 0.5. The second order wave function was expressed in formula (11). The parameter values were set as follows: the gain constant $K_\omega = 0.42$, the dominant wave frequency $\omega_0 = 0.606$, the damping coefficient $\zeta = 0.3$.

$$h(s) = \frac{K_\omega s}{s^2 + 2\zeta \omega_0 s + \omega_0^2}$$ (11)

The disturbance signal in simulation experiment was shown in Fig. 6. In case of external disturbance, the controlling effect of two heading controllers was shown in Fig. 7, and the correspondent variation of steering-angle control quantity was shown in in Fig. 8.
From the simulation results in Fig. 8 and Fig. 9, it could be seen that, in the presence of external wave and wind disturbance, the control effect of PFC-based USV heading control system were superior to the classic PID-based control system. Indicated by the course tracking curve in Fig. 8, the PFC-based heading control system was able to track the objective course at a faster rate; furthermore, it reflected less jitter in course when tracking the target course [9]. From the variation curve of steering-angle control quantity in Fig. 9, it indicated that PFC-based heading controller possessed smoother variation in output steering-angle control quantity.

4.2. Course Tracking Effect

Under ideal circumstances of no disturbance, it undertook simulation experiment on course tracking
effect of the two heading control systems. In the simulation experiment, it input a sine signal of magnitude and 0.02 rad/s frequency on the given objective heading angle of USV. The course tracking effect of two kinds of controllers that was acquired in the simulation experiment was shown in Fig. 9. The variation curve of steering-angle control quantity was shown in Fig. 10.

![Fig. 9 Course tracking effect(without interference)](image9)

![Fig. 10 Steering-angle control quantity in course tracking (without interference)](image10)

To further analyze the controlling effect of PID-based heading controller versus PFC-based heading controller, the mean tracking error of both controller courses was given respectively in Tab. 2. From Fig. 9, Fig. 10 and Tab. 2, it showed that, the PFC-based heading controller had stable course tracking performance; more than that, both its tracking speed and tracking precision were higher than traditional PID-based heading controller.

| Controller | Mean course tracking error |
|------------|---------------------------|
| PID        | 4.9180°                   |
| PFC        | 3.4953°                   |

In case of external disturbance, a sine signal of 90° amplitude and 0.02 rad/s frequency was input into the objective heading angle of given USV to simulate the course tracking effect on both types of heading controllers. It still used the wind and wave interference stated in formula (11) as the disturbance signal, which was shown in Fig. 6. The acquired course tracking effect was shown in Fig. 11. The variation of steering-angle control quantity was shown in Fig. 12. 

![Tab. 2 Course tracking error](image2)
To further analyze the controlling effect of PID-based heading controller versus PFC-based heading controller, the course tracking errors of both controllers were given in Tab. 3. As was shown in Fig. 11, Fig. 12 and Tab. 3, the PFC-based heading controller was still able to retain stable course tracking properties in case of disturbance. Moreover, its tracking speed and precision were both higher than traditional PID-based heading controller.

| Controller | Mean tracking error |
|------------|---------------------|
| PID        | 4.9384°             |
| PFC        | 3.5001°             |

**5. Conclusions**

Based upon the principle of predictive function control algorithm as well as combining with the requirements of USV heading control, it presented a kind of PFC-based surface USV heading controller. Through contrastive simulation experiments on heading retention and course tracking between this heading controller and the surface USV heading controller that was designed by classic PID algorithm, it validated that the heading controller based upon predictive function control algorithm possessed more favorable performance in heading retention and course tracking.

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