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Model Predictive Controller Design with Disturbance Observer for Path Following of Unmanned Surface Vessel

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***Abstract* - A model predictive controller with disturbance observer is presented to force an automated unmanned surface vessel (USV) to follow a reference path with environment disturbance. A full-scale trials by fully instrumented USV is carried out to identify the dynamic model. The Serret-Frenet frame is used to define the tracking error, therefore the position tracking errors can be stabilized by stabilizing the state of the control model to zero. And the constrained control input of the considered system is solved by minimizing performance based on model predictive control (MPC). Simulation and experiments results are presented to validate the effectiveness of the proposed method.**

Index Terms - USV, Path Following, Predictive Control, Disturbance Observer.

I. Introduction

Over the last years, Unmanned control of surface vessel is the hotspot in the areas of control all along, and the path following problem of USV has received a lot of attention from the control community [1-7]. Conventional surface vessels are usually equipped with one or two main propellers and a rudder, the main propeller is used to provide propulsion to make the ship move straight forward at a fixed speed, the rudder is used to control the direction of the ship. The early development of the intelligent control with surface vessel is focus on the autopilot [1], it makes the ship move toward the target point by changing the course only. The autopilot method usually has a PID control system using line-of-sight (LOS) method [2]. The path following problem consists of stabilizing the system about a prescribed path, without any time specifications, i.e. without specifying when the ship is to be at a given point at this path. So the ship can follow the target point by only changing the heading of the ship [3]. Due to no path control in the control process, the PID control algorithm cannot deal with the interference well. At the same time, there will be a lot of useless or inefficient operation in the control process.

To solve the problem above, a trajectory tracking control system which based on the coordinate and ship maneuvering mathematical model was proposed. But the challenges of it are the complex nonlinearity of the kinetic model and the kinematic model. Due to the disturbance of wind, wave and current, and the physical model of the ship itself, the path tracking model of the ship is high nonlinear and strong coupling, and is very complex to design the controller. Note that in literature the terms path following, tracking and maneuvering are used interchangeably. Do KD [4] designed a nonlinear controller based on backstepping and Lyapunov direct method in the coordinate of the given path. Tieshan Li and Yanshen Yang [5] designed a nonlinear controller based on the integral backstepping adaptive control, the dissipative theory and the linearization of input and output. Qian Zhou [6] linearized the path following control model by fuzzy control in some part, and then designed a sliding mode controller. In order to guarantee the stability of the system, Lan Zhou [7] proposed a method which redefined and linearized the input and output variable.

However, these researches above seldom consider about the disturbance of wind, wave and current. Meanwhile, some of the methods will lead to the violent fluctuation of the rudder angle. This will cause the shaking of the ship and will be the threat to people or goods on ship. So these methods are not suitable for the real ship. For that reason, a path following control method using predictive control based on state equation is put forward. It can reduce the impact of the environment disturbance and provide the smooth control commands by using third-order model predictive control law with disturbance observer. We used it on a fully instrumented USV named HEU-3 and the results of the real-boat marine trials show that the MPC can deal with the path following problem in the real marine environment very well.

II. PROBLEM DESCRIPTION

A. Path Following Problems

Fig. 1 shows the Serret-Frenet frame used for path following control. The origin of the frame {SF} is located at the closest point on the given path from the origin of the body-fixed frame {B}. The error dynamics based on the Serret-Frenet equations [8] are given by:

$$\begin{cases} \dot{e} = u\sin(\bar{\psi}) + v\cos(\bar{\psi}) \\ \dot{\bar{\psi}} = \dot{\psi} - \dot{\psi}_{SF} = \dfrac{\kappa}{1-e\kappa}\left(u\sin(\bar{\psi}) - v\cos(\bar{\psi})\right) + r \end{cases} \tag{1}$$

where e, defined as the distance between the origins of {SF} and {B}, is referred to the cross-track error. And ψ is the heading angle of the ship, ψ_{SF} is the path tangential direction as shown in Figure.1, And $\bar{\psi}$ is the heading error and it is defined as $\bar{\psi} = \psi - \psi_{SF}$, u is the surge, v is the sway, r is yaw velocity, κ is the curvature of the given path Ω. T and N in Figure.1 are the tangent and normal directions of the given path Ω at the origin of {SF}.

The control objective of the path following problems in Serret-Frenet frame is to drive e and $\bar{\psi}$ to zero [9]. When environmental disturbance (such as wind, wave and current) exist, the path following e and $\bar{\psi}$ can not be eliminated at the same time. In such circumstances, the primary objective is to maintain a small or near-zero cross-track error e, while keeping certain necessary heading error $\bar{\psi}$ to counteract the environment disturbance.

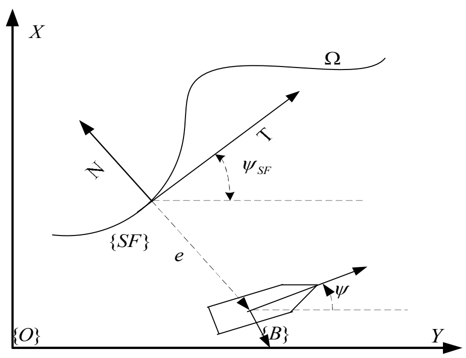


Fig. 1 Illustration of the coordinates in the earth frame (inertial frame) {O}, the surface vessel body-fixed frame {B} and the Serret-Frenet frame {SF}

For most of the path following problem, the given path is a straight line or a way-point path, which consists of piecewise straight lines with the curvature κ being zero. Even though the curvature is not zero, we can also segment it into lots of piecewise straight lines. Through the method above, the error dynamics can be simplified as follow:

$$\begin{cases} \dot{e} = u\sin(\bar{\psi}) + v\cos(\bar{\psi}) \\ \dot{\bar{\psi}} = r \end{cases} \tag{2}$$

In practice however, the surge speed is much greater than the sway speed. Therefore, the U, speed of the ship, can be approximated as $U = \sqrt{u^2 + v^2} \approx u$. The primary objective is nevertheless the geometric task, which is perfectly achievable. According to the equation {2}, we can get:

$$\begin{cases} \dot{e} = U\sin\bar{\psi} \\ \dot{\bar{\psi}} = r \end{cases} \tag{3}$$

B. Control Model

The linear equation of ship's yaw in this paper is the 1st-order Nomoto model [10] except for less affected parameters. 1st-order Nomoto model related to the velocity of yaw and the rudder angle is defined as follows:

$$T\dot{r} + r = K\delta \tag{4}$$

Where $r = \dot{\psi}$ is yaw rate, ψ is yaw angle, K and T are maneuvering indices [11][12][13]. Considering the environment disturbance and model mismatch, the 1[st]-order Nomoto model can be expressed as follows:

$$T\ddot{\psi} + \dot{\psi} = K\delta + d(t) \tag{5}$$

Where $d(t)$ is the low-frequency disturbances caused by wind, current, and wave forces, that satisfies $|d(t)| \le d_{\max}(t)$, $|\dot{d}| \le \xi$. By combining equation (6) and equation (3), we can get the nonlinear mathematical model of the ship's path following control system:

$$\begin{cases} \dot{e} = u\sin\bar{\psi} \\ \dot{\bar{\psi}} = r \\ \dot{r} = -\dfrac{1}{T}r + \dfrac{K}{T}\delta + d(t) \end{cases} \tag{6}$$

Before proceeding to the controller design, an additional assumption can be made to further simplify the model. In ship maneuvering, we assume that yaw angle ψ is relatively changing around zero, which means $\sin\bar{\psi} \approx \bar{\psi}$. With this assumption, the final model for control design, that captures the dominant ship maneuvering dynamics and path following error dynamics, with one control variable δ, has been simplified into:

$$\begin{bmatrix} \dot{r} \\ \dot{\bar{\psi}} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{T} & 0 & 0 \\ 1 & 0 & 0 \\ 0 & U & 0 \end{bmatrix} \begin{bmatrix} r \\ \bar{\psi} \\ e \end{bmatrix} + \begin{bmatrix} \dfrac{K}{T} \\ 0 \\ 0 \end{bmatrix} \delta + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} d(t) \tag{7}$$

The equation (8) is the control model used in this paper for path following problem. By calculating the rudder input δ, we drive the state variables of the equation (8) into zero, so that the ship can track the given path.

III. CONTROLLER DESIGN

A. The design of disturbance observer

In order to estimate the disturbance part $d(t)$ in (8), we design a disturbance observer as follow steps:

First, we write the equation (8) to the form of common linear system:

$$\begin{cases} \dot{x} = f(x) + g_1(x)u + g_2(x)d \\ y = h(x) \end{cases} \tag{8}$$

Where, $x = [r\ \bar{\psi}\ \mathrm{e}]^T$ is the state variables of the system. u is input, d is disturbance and $\dot{d} = 0$. Output of the system is $y = h(x) = Cx$. $g_1(x) = [b_1\ 0\ 0]^T$ is control matrix, $g_2 = [1\ 0\ 0]^T$ is the disturbance matrix. According to the equation (9), we get:

$$g_2(x)d = \dot{x} - f(x) - g_1(x)u \tag{9}$$

By introducing the auxiliary variable z, the disturbance observer [14] are designed as follows:

$$\begin{cases} \hat{d} = z + p(x) \\ \dot{z} = -l(x)z - l(x)(p(x) + f(x) + g_1(x)u) \end{cases} \tag{10}$$

where $l(x) = \partial p(x)/\partial x$ is the gain matrix of the disturbance observer, $p(\boldsymbol{x}) = [l_1\ l_2\ l_3][x_1\ x_2\ x_3]^{\mathrm{T}}$, and $\hat{d}$ is the estimation of d.

Define the estimation error of disturbance observer as

$$\begin{cases} e_1 = d - \hat{d} \\ \dot{e}_1(t) = \dot{d} - \dot{\hat{d}} = l(x)g_2(x)(\hat{d} - d) = -l(x)g_2(x)e_1(t) \end{cases} \tag{11}$$

It can be shown the $\hat{d}$ approaches d if $l(x)$ is chosen such that

$$\dot{e}_1(t) + l(x)g_2(x)e_1(t) = 0 \tag{12}$$

is globally exponentially stable for all $x \in R^n$. As far as the stability of the estimation error is concerned, any nonlinear vector valued function $l(x) = \partial p(x)/\partial x$, such that (12) is asymptotically stable, can be chosen. Having chosen $l(x)$, $p(x)$ is found by integration.

B. The design of MPC controller based on disturbance observer

MPC is widely used in control area in recent years [15-16], but most application of the MPC in path following problem of ships are in simulation environment, and there are few MPC applications on real ship trail. In real ship environment, there will always be the disturbance and the ship's mechanical error. The common nonlinear algorithm cannot deal with this problem well. But the MPC which consists of the predictive model, rolling optimization and feedback compensation can do it better. In this paper, we add the nonlinear disturbance observer defined in section III into MPC algorithm, so that we can improve robustness of control system.

For notational convenience, the equation (8) is rewritten as:

$$\begin{cases} \dot{x} = Ax + Bu + gd \\ y = Cx \end{cases} \tag{13}$$

Where x is the state variable, u is the control input, d is the disturbance, y is the output, A, B, C are the system matrices, g is disturbance matrix.

By discretizing the equation (13) we can get:

$$\begin{cases} x(k+1) = A_k x(k) + B_k u(k) + g_k d(k) \\ y(k) = C_k x(k) \end{cases} \tag{14}$$

The MPC design requires the predicted future outputs for a Number of steps ahead, where these are generated from the state-space model at the current sampling instant. Let $x(k+i\,|\,k)$, $u(k+i\,|\,k)$ and $y(k+i\,|\,k)$ denote the corresponding vectors in (14) at sample instant $k+i$ given them at sample instant k. Then the state dynamics N_P sampling instant ahead of k are given by

$$\begin{cases} x(k+1\,|\,k) = A_k x(k) + B_k u(k) + g_k d(k) \\ x(k+2\,|\,k) = A_k^2 x(k) + A_k B_k u(k) + B_k u(k+1) + \\ \qquad A_k g_k d(k) + g_k d(k+1) \\ \vdots \\ x(k+N_p\,|\,k) = A_k^{N_P} x(k) + A_k^{N_P-1} B_k u(k) + \cdots + \\ \qquad A_k^{N_P-N_C} B_k u(k+N_c-1) + A_k^{N_P-1} g_k d(k) + \\ \qquad \cdots + A_k^{N_P-N_C} g_k d(k+N_c-1) \end{cases} \tag{15}$$

Where N_P and N_c are termed the prediction and control horizons, respectively. Also the choice $N_c \le N_p$ assumes that the control $u(k)$ has reach the steady-state after N_c instants.

The predicted output vectors for the next N_P instants can be written in the compact form:

$$Y = Fx(k) + \Phi U + TD \tag{16}$$

where $Y = [y^T(k+1)\quad y^T(k+2)\quad \cdots\quad y^T(k+N_P)]^{\mathrm{T}}$,
$U = [u^T(k)\quad u^T(k+1)\quad \cdots\quad u^T(k+N_P-1)]^{\mathrm{T}}$,
$F = [(C_k A_k)^T\quad (C_k A_k^2)^T\quad \cdots\quad (C_k A_k^{N_P})^T]^{\mathrm{T}}$
$D = [d^T(k)\quad d^T(k+1)\quad \cdots\quad d^T(k+N_P-1)]^{\mathrm{T}}$,

$$\Phi = \begin{bmatrix} C_k B_k & 0 & \cdots & 0 \\ C_k A_k B_k & C_k B_k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ C_k A_k^{N_P-1} B_k & C_k A_k^{N_P-2} B_k & \cdots & C_k A_k^{N_P-N_C} B_k \end{bmatrix},$$

$$T = \begin{bmatrix} C_k g_k & 0 & \cdots & 0 \\ C_k A_k g & C_k g_k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ C_k A_k^{N_P-1} g & C_k A_k^{N_P-2} g & \cdots & C_k g_k \end{bmatrix}.$$

The cost function used for the MPC design has the structure

$$\begin{aligned} \bar{J} = &\sum_{i=1}^{N_p} [y_d(k+i) - y(k+i\,|\,k)]^{\mathrm{T}} \bar{Q}\, [y_d(k+i) - y(k+i\,|\,k)] + \\ &\sum_{i=1}^{N_c} \bar{R}\, [u(k+i-1\,|\,k)]^2 + \sum_{i=1}^{N_p} H[D(k+i-1\,|\,k)]^2 \end{aligned} \tag{17}$$

where $\bar{Q}$ 、 $\bar{R}$ 、 H are all positive symmetric matrix.

For notational convenience, we rewrite the equation (17) as follows:

$$\bar{J} = (Y_d - Y)^T \bar{Q} (Y_d - Y) + U^T \bar{R} U + D^T H D \tag{18}$$

Under the receding horizon principle, the control vectors for the next N_c sampling instants are obtained by minimizing the cost function (18) but only the first of these is applied to the plant. In the absence of constraints the global optimal solution is given by $\bar{J}$ by $\partial \bar{J}/\partial U = 0$, and solving this equation gives the global optimal control sequence as

$$U = (\Phi^T \bar{Q} \Phi + \bar{R})^{-1} [\Phi^T \bar{Q} (Y_d - Fx(k) - TD)] \tag{19}$$

The control problem with disturbance and input constraint can be described as below:

$$\min \bar{J}$$
$$s.t.\begin{cases}\bar{J}=(Y_d-Y)^T\bar{Q}(Y_d-Y)+U^T\bar{R}U+D^THD \\ Wu\le r\end{cases} \tag{20}$$

At every sampling time, we get the control sequence U below by minimizing the new cost function $\bar{J}$:

$$U=(\Phi^T\bar{Q}\Phi+\bar{R})^{-1}[\Phi^T\bar{Q}(Y_d-Fx(k)-TD)-\frac{1}{2}W^T\gamma^*] \tag{21}$$

We take the first one of the vector U as the control rudder, so we can get the control law as:

$$\begin{aligned}\delta_{mpc}(k)&=[I\ 0\ 0\ ...0]U=[I\ 0\ 0\ ...0](\Phi^T\bar{Q}\Phi+\bar{R})^{-1}\\ &[\Phi^T\bar{Q}(Y_d-Fx(k)-TD)-\frac{1}{2}W^T\gamma^*]\end{aligned} \tag{22}$$

where $D=\hat{D}=[\hat{d}^T(k)\quad \hat{d}^T(k+1)\quad \cdots\quad \hat{d}^T(k+N_P-1)]^{\mathrm{T}}$ is the online estimated value of nonlinear disturbance obtained from the disturbance observer.

IV. Experimental Test-bed Introduction

A. USV introduction

To support the control development, a fully instrumented USV was designed so that the controller proposed in Section 3 could be experimentally evaluated. The USV is equipped with a main propeller and a rudder. The main propeller is actuated by a brushless DC motor (1kW). The rudder is actuated by two DC servo motors and a co-load dual axis system. The DC servo motors drive the dual-axis system to rotate, so that the dual-axis will make the rudder rotate to change the heading of the USV. The main parameters of the USV are given in Table I:

TABLE I
Principal particulars of the USV

Item	Symbol	Value
Length	L	2.20m
Beam	B	0.67m
Draft	H	0.56m
Mass	m	67kg
Inertia	I2	5.4kgm2

The real-time feedback controller is working on a slave IPC with VS2010 based WinXP operation system. The software connects with GPS and motor drive model by RS232 serial port, so that it can get the position and attitude of the USV, and control the propeller and the rudder. In addition, there is a host computer working on the shore and connect with the slave computer through wireless data transfers. The main functions of host computer is starting or stopping the slave IPC, choosing the working model. The slave computer software will send the states of the USV to host upper computer in real time. A handheld terminal controller is instrumented for emergency braking if the auto-control system is out of control. The control system block diagram and the picture of the USV are showing as follows:

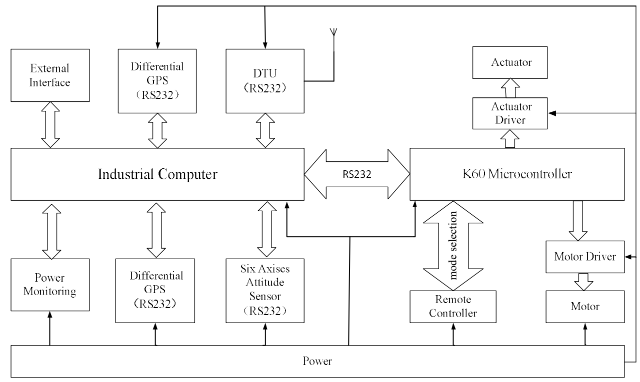


Fig. 2 The control system block diagram of the USV


Fig. 3 The picture of the USV

B. Identification of Parameters

Consider mathematical model of USV defined as equation (8) with parameter U, K and T. In practice, the surge speed is much greater than the sway speed. Therefore, the U, speed of the ship, is constant and can be measured from GPS. System identification combined with turning test and zigzag test is one of the effective methods to determine K and T.

The Circle-running Test: Firstly, control the USV to sail with a constant rudder angle in a constant speed. Secondly, record the information of yaw and rudder angle when the USV is running along a circular path.

The zigzag test: Keep the USV moving straightforward at a constant speed. Then turn the rudder periodically at a constant angle. Simultaneously, record the information of yaw and rudder angle when the USV is running along a zigzag path.

The experimental results of circle-running and zigzag test are shown as follows:

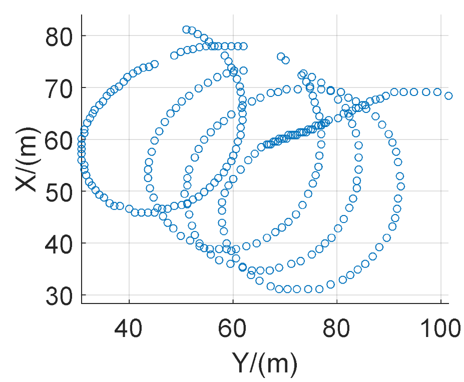
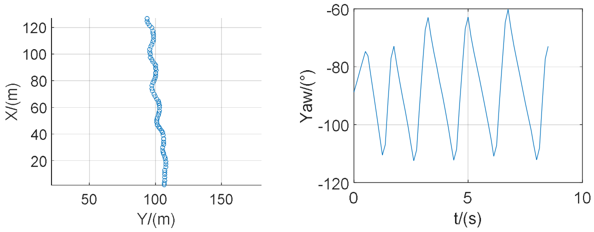


Fig. 4 Data of Turning Test at 15°rudder angle



(a) (b)

Fig. 5 Zigzag test at ±15°periodical rudder angle

Fig. 4 shows the track of Turning Test at 15°rudder angle, and Fig. 5(a) shows the track of zigzag test at $\pm 15^{\circ}$ periodical rudder angle, and Fig. 5(b) shows the yaw of zigzag test at $\pm 15^{\circ}$ periodical rudder angle.

The formulas of how to get the parameters in KT model are given as follows:

$$\dot{\psi}(k) = [\varphi(k+1) - \varphi(k-1)]/(2h) \tag{23}$$

$$\ddot{\psi}(k) = [\varphi(k+1) - 2\varphi(k) + \varphi(k-1)]/h^2 \tag{24}$$

$$\dddot{\psi}(k) = [\varphi(k+2) - 2\varphi(k+1) + 2\varphi(k-1) - \varphi(k-2)]/(2h^3) \tag{25}$$

where h is sampling time. According to the formulas above, we can get the $\dot{\psi}$ and $\ddot{\psi}$ in equation (6), so that we can get:

$$K = \dot{\psi}/\delta \tag{26}$$

$$T = (K\delta - \dot{\psi})/\ddot{\psi} \tag{27}$$

By using the equation (23)-(27), we can calculate the ψ , $\dot{\psi}$, K and T in every time, and at last we average the K and T to get the ultimate K and T.

In this paper, by using method introduced above, selecting cruising speed U=1.55m/s, the parameters of the USV are identified as follows: K=24.1592 , T=0.4073 .

V. RESULTS

A. Simulation Result

Using the control method mentioned, a tracking simulation based on MPC is proposed as follows. The sampling time is $T = 0.08$s , the prediction horizon is $N_P = 3$, the control horizon is $N_C = 1$. The disturbance is the sinusoidal interference (amplitude is 2 and frequency is 0.1.) The initial states are defined as $(r, \bar{\psi}, e) = (0, -45/57.3, 15)$. The desired trajectory is a straight line.

In order to compare the influence of different $\bar{Q}$ and $\bar{R}$, we choose different $\bar{Q}$ and $\bar{R}$ in the simulation. The results are shown as Fig. 6, where Fig. (6-a) is the position tracking errors, Fig. (6-b) is the response of yaw, Fig. (6-c) is the response of yaw velocity, Fig. (6-d) is the trajectories when Q=5 , R=5.

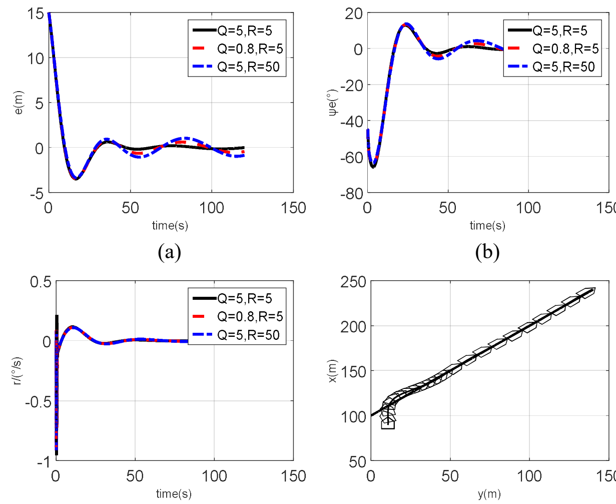


Fig. 6 The results of MATLAB simulation

B. The real-boat trial Test Result

Although the performance of the path following control law proposed in this paper has been verified by the MATLAB simulation in above, while the results are output from the designed ideal simulation scenes which are different from the real situation of real ship in the real marine environment. In order to verify the related performance of the MPC control law on the real vessel in the real marine environment, we have done real-boat marine trials in river. In the real marine environment, the desired trajectory is often a straight line or a way-point path [17]. In this trial, the desired trajectory is the red line in Fig. 8, it is made up of the way-point path, obviously. The trajectory data of the USV was measured by GPS. For convenience, the unit has been converted into *m*. The result of the real-boat marine trials is shown by the blue line in Fig. 8, it indicates that the control system we designed in this paper can deal with the path following problem in the real marine environment very well.


Fig. 7 The real-boat marine trial

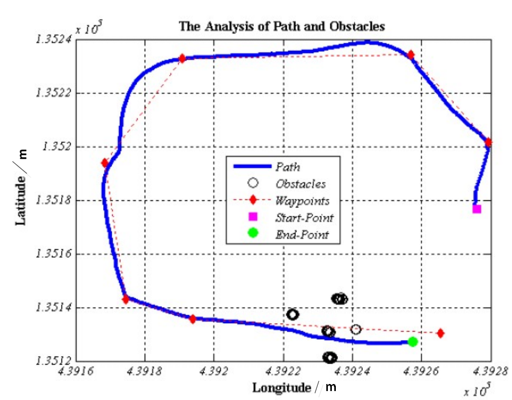


Fig. 8 The result of the real-boat marine trial

V. CONCLUTION

The motion control of the underactuated USV faces the nature nonlinear, strong coupling and nonlinear processing problems. We studied the real-boat path following problem at a constant speed in this paper. In this situation, the common control methods cannot deal with the disturbance and the model mismatch problem, or the control models of them are very complex. So this paper presents a MPC straight-line path following control algorithm based on the Nomoto's model to solve these problems. We got the K and T of the USV by experiments, and then we got the control model. We designed the MPC control algorithm with disturbance observer described as equation (10). The simulation results show that it can solve the path following problem. In order to verify the related performance of the algorithm, we designed the real-boat marine trials in river. The results indicated that the algorithm can deal with the path following problem in the real marine environment very well. However, the results of the real-boat marine trials also show that there are still some errors near some way point and in some path. To solve this problem, we should promote the accuracy of the disturbance observer.

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REFERENCES

[1] CHENG Qiming, LIU Qiming, WANG Zhihong, UN Ganchao. The Study on Development of the Control Techniques on Ship Autopilot [J]. COMPUTER AUTOMATED MEASUREMENT & CONTROL, 2000, vol.8(6), pp. 1-4.

[2] Pettersen K Y, Egeland O. Exponential stabilization of an underactuated surface vessel[C], Decision and Control, 1996. Proceedings of the 35th IEEE. IEEE, 1996, vol. 1, pp. 967-972.

[3] YANG Yan-sheng, YU Xiao-li, JIA Xin-le. Robust PID autopilot for ships [J]. JOURNAL OF DALIAN MARITIME UNIVERSITY, 1999, vol. 4, pp. 11-15.

[4] Do, KD (Do, K. D.), Global path-following control of underactuated ships under deterministic and stochastic sea loads. ROBOTICA, vol. 34 (11), pp. 2566-2591,2016.

[5] LI Tie-shan YANG Yan-sheng. A Robust Design Based on the Dissipation Theory for the Linear-Course Trajectory Control of Underactuated Ships [J]. JOURNAL OF APPLIED SCIENCES, 2005, vol. 23(2), pp. 204-207.

[6] ZHOU Qian, SONG Li-zhong, YAO Qiong-hui. Design of sliding mode controllers for ship's track-keeping control systems based on linearized models [J]. JOURNAL OF NAVAL UNIVERSITY OF ENGINEERING, 2007, vol. 19(l), pp. 99-104.

[7] ZHOU Gang, YAO Qiong-Hui, CHEN Yong-Bing, ZHOU Yong-Yu, Li Wen-Kui. A Study of Stability of Straight-line Tracking Control System for Underactuated Ship [J]. ACTA AUTOMATICA SINICA, 2007, vol. 33(4), pp. 378-383.

[8] R. Skjetne and T. I. Fossen. Nonlinear maneuvering and control of surface vessels. Proceedings of the MTS/IEEE OCEANS, 2001.

[9] L Lapierre, D Soetanto, and A Pascoal. Nonlinear path following with applications to the control of autonomous underwater vehicles[C]. Proceeding 42nd IEEE Conference on Decision and Control,2003, vol. 2, pp. 1256– 1261.

[10] SUN Jian-gang, DENG De-heng, HUANG Guo-liang. A Study of Sensitivity of Surface Ship Maneuverability [J]. NAVIGATION OF CHINA, 2006, vol. 66(1), pp. 49-52.

[11] Jia Xinle, Yang Yanshen. Mathematical Model of Ship Movement: Mechanism Modeling and Identification Modeling [M].Dalian: Dalian Maritime University Press, 1999.

[12] Zhang Xianku, Jia Xinle, Liu Chuan. Research on responding ship motion mathematical model [J]. JOURNAL OF DALIAN MARITIME UNIVERSITY, 2004, vol. 30(1), pp. 18-21.

[13] T I Fossen. Guidance and control of ocean vehicles [M]. John Wiley and Sons, Inc., 1994.

[14] W.H.Chen, D.J.Ballance, P.J.Gawthrop. Nonlinear PID predictive controller. IEE Proceedings: Control Theory and Applications, 1999, vol. 146(6), pp. 603-611

[15] Xi Yugeng. Predictive Control (2nd Edition)(M). Beijing:National Defense Industry Press, 2013.

[16] Shan Chai, Liuping Wang, Eric Rogers. Model predictive control of a permanent magnet synchronous motor with experimental validation. Control Engineering Practice. Vol.21,pp.1584–1593,2013.

[17] T. Holzhuter. LQR approach for the high-precision track control of surface vessels. IEEE Proceedings of Control Theory and Applications, vol. 144(2), pp. 121–127, 1997.