Command Filtered Backstepping Control for Dynamic Positioning Ships

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Abstract—**Taking the dynamics of the thruster increases the order of the ship motion model and makes it difficult for researchers to obtain the derivative of the virtual control signal, and meanwhile the derivative complicates the control law for its complexity. A filter, which can approximate the virtual control signal and its derivative, is introduced to the backstepping controller design to avoid the derivation process and simplify the controller design. While the model parameters are unknown, an adaptive fuzzy logic system is utilized to estimate the unknown nonlinear functions which are necessary for the control law. It can compensate the system uncertainties and unmodeled dynamics due to its robustness. The closed-loop system is proved to be uniformly ultimate bounded by Lyapunov stable theory and simulation results verify the stability and effectiveness of the proposed controller.**

Keywords—Command Filtered Backstepping; Uniformly Ultimate Bounded; Surface Ships

I. INTRODUCTION

Dynamic positioning technique is becoming more and more important in overseas exploring and rescuing, as more and more researchers are concerning on the marine engineering and development. As the motion of a ship in the sea shows strong nonlinear and coupling, and also the parameters of a ship is difficult to decide, so how to design a proper controller for the motion of a ship has becoming one of the challenging problem in the ship control area.

In recent years, researchers have designed different control strategies for dynamic positioning systems, such as model predictive control, Active Disturbance Rejection Control, neural networks, etc. Guoqing Xia, et al proposed DRNN based PD hybrid controller by combining neural network and PID to improve the robustness and precision of the controller. Zhiliang Deng et al introduced online support vector regression technique into model predictive control, and the proposed online model predictive controller was shown to be good robustness. Yuanhui Wang et al designed nonlinear model predictive controller by combining Lie derivatives and correlation degree, and validated its effectiveness in simulations. Dawei Zhao et al designed dynamic positioning control algorithm based on Active Disturbance Rejection technique, and the simulation results showed the strong capacity of disturbance resistance and robustness. Qidan Zhu et al designed sliding mode robust controller with strong robustness.

As backstepping method is simple in its design procedure and form, the algorithm is widely used in the design of nonlinear ship motion control area. However, when the order of a model increases, the backstepping method needs to calculate the derivatives of the virtual control variables, which will make the design procedure complex. Meanwhile, backstepping method is no longer applicable when the parameters of the model is unknown.

In this paper, the adaptive control algorithm based on filtered backstepping method is proposed, with the dynamics of the thrusters considered. A filter, which can approximate the virtual control signal and its derivative, is introduced to the backstepping controller design to avoid the derivation process and simplify the controller design. The derivation procedure is replaced by the integral effect of the filter, so the controller has inhibition effect on the noises. The closed-loop system is proved to be uniformly ultimate bounded by Lyapunov stable theory

II. SHIP MODELLING

Before the establishment of ship mathematical model, we should establish the coordinate system. That is the earth fixed frame $X_E Y_E Z_E$ and the body fixed frame XYZ and the definition of frame system is shown in Fig.1.

As the mentioned in the articles of [13, 14], the kinematics and dynamics model of surface ship is

$$\dot{\boldsymbol{\eta}} = \mathrm{R}(\boldsymbol{\eta})\mathbf{v} \tag{1}$$

$$\mathbf{M}\dot{\mathbf{v}} + \mathrm{C}(\mathbf{v})\mathbf{v} + \mathrm{D}(\mathbf{v})\mathbf{v} = \boldsymbol{\tau} + \mathrm{J}^{\mathrm{T}}(\boldsymbol{\eta})\mathrm{b} \tag{2}$$

where $\boldsymbol{\eta} = \left[x, y, \psi\right]^{\mathrm{T}}$, $\mathbf{v} = \left[u, v, r\right]^{\mathrm{T}}$ represent the ship position vector and the velocity vector respectively. x, y are the position coordinate in the earth fixed frame. ψ is the heading angle. u, v, r represent the surge, sway and yaw velocities in the body fixed frame. $\boldsymbol{\tau} = [\tau_x, \tau_y, \tau_\psi]^{\mathrm{T}}$ is the commanding order of controller. $\mathbf{M}$ is inertia matrix including the added mass. $\mathrm{C}(\mathbf{v})$ is the is the matrix of Coriolis and centripetal force. $\mathrm{D}(\mathbf{v})$ is the damping matrix of ship and

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$D(\mathbf{v})=D_l+D_n(\mathbf{v})$, where the D_l is the linear damping matrix and the $\mathbf{D}_n(\mathbf{v})$ is the nonlinear damping matrix. b is the vector of slowly varying environment force and moment, mainly caused by wind, current and wave.

$J(\boldsymbol{\eta})$ is the coordinate translating matrix based on the heading of ship and is represented as:

$$J(\boldsymbol{\eta})=J(\psi)=\begin{bmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}.$$

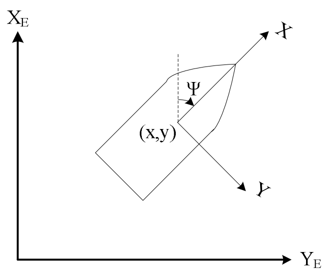

Fig.1.The earth fixed frame $X_E Y_E Z_E$ and the body fixed frame XYZ

The matrix $J(\boldsymbol{\eta})$ is nonsingular to all of the output $\boldsymbol{\eta}$, and $J(\boldsymbol{\eta})J(\boldsymbol{\eta})^{T}=\mathbf{I}$, $\mathbf{I}$ is the identity matrix. That is $J(\boldsymbol{\eta})^{T}=J(\boldsymbol{\eta})^{-1}$.

Usually, the matrices $\mathbf{M}$, $C(\mathbf{v})$ and $D(\mathbf{v})$ are very difficult to determine, because of the parameter uncertainty and the modelling error. Considering of the effect of unmodeled dynamics, the ship kinematics model is represented as:

$$\mathbf{M}\dot{\mathbf{v}}+C(\mathbf{v})\mathbf{v}+D(\mathbf{v})\mathbf{v}=\boldsymbol{\tau}+J^{T}(\boldsymbol{\eta})b+\boldsymbol{\omega} \tag{3}$$

where $\boldsymbol{\omega}$ is the unmodeled dynamics term, and the matrix coefficients are described as: $\mathbf{M}=\mathbf{M}^{*}+\Delta\mathbf{M}$, $C(\mathbf{v})=C^{*}(\mathbf{v})+\Delta C(\mathbf{v})$, $D(\mathbf{v})=D^{*}(\mathbf{v})+\Delta D(\mathbf{v})$. The symbol '$*$' represents the nominal value of corresponding matrix, the symbol 'Δ' is the matrix uncertainty parameters.

In order to use the back-stepping method, the ship model is translated as:

$$\dot{\mathbf{x}}_1=\mathbf{x}_2 \tag{4}$$

$$\begin{aligned}\dot{\mathbf{x}}_2=&\mathbf{M}_{\eta}^{-1}(\mathbf{x}_1)(\mathbf{u}+J\boldsymbol{\omega})-\mathbf{M}_{\eta}^{-1}(\mathbf{x}_1)C_{\eta}(\mathbf{x}_1,\mathbf{x}_2)\mathbf{x}_2\\ &-\mathbf{M}_{\eta}^{-1}(\mathbf{x}_1)D_{\eta}(\mathbf{x}_1,\mathbf{x}_2)\mathbf{x}_2+\mathbf{M}_{\eta}^{-1}(\mathbf{x}_1)b\end{aligned} \tag{5}$$

where $\mathbf{x}_1=\boldsymbol{\eta}$, $\mathbf{x}_2=\dot{\boldsymbol{\eta}}$, $u=J^{-T}(\boldsymbol{\eta})\boldsymbol{\tau}$ and

$$\mathbf{M}_{\eta}(x_1)=\mathbf{J}^{-T}(\boldsymbol{\eta})\mathbf{M}\mathbf{J}^{-1}(\boldsymbol{\eta})$$
$$C_{\eta}(x_1,x_2)=\mathbf{J}^{-T}(\boldsymbol{\eta})[C(\mathbf{v})-\mathbf{M}\mathbf{J}^{-1}(\boldsymbol{\eta})\dot{\mathbf{J}}(\boldsymbol{\eta})]\mathbf{J}^{-1}(\boldsymbol{\eta})$$
$$D_{\eta}(x_1,x_2)=\mathbf{J}^{-T}(\boldsymbol{\eta})D(\mathbf{v})\mathbf{J}^{-1}(\boldsymbol{\eta}).$$

Considering the dynamic character of thrusters and taking the thrusters as the first order inertial element. Thus, the model is written as:

$$\dot{\boldsymbol{\tau}}=\bar{\mathbf{A}}\boldsymbol{\tau}+\bar{\mathbf{B}}\boldsymbol{\tau}_e \tag{6}$$

where, $\bar{\mathbf{A}}$ and $\bar{\mathbf{B}}$ are the diagonal matrix of corresponding dimension. $\boldsymbol{\tau}_e$ is the commanding order. Therefore,

$$\begin{aligned}\dot{\mathbf{u}}&=J^{-T}(\boldsymbol{\eta})\dot{\boldsymbol{\tau}}+\dot{J}^{-T}(\boldsymbol{\eta})J^{T}(\boldsymbol{\eta})\mathbf{u}\\ &=J^{-T}(\boldsymbol{\eta})\bar{\mathbf{A}}J^{T}(\boldsymbol{\eta})\mathbf{u}+J^{-T}(\boldsymbol{\eta})\bar{\mathbf{B}}\boldsymbol{\tau}_e+\dot{J}^{-T}(\boldsymbol{\eta})J^{T}(\boldsymbol{\eta})\mathbf{u}\\ &=\mathbf{A}\mathbf{u}+\mathbf{B}\boldsymbol{\tau}_e\end{aligned} \tag{7}$$

where, $\mathbf{A}=J^{-T}(\boldsymbol{\eta})\bar{\mathbf{A}}J^{T}(\boldsymbol{\eta})+\dot{J}^{-T}(\boldsymbol{\eta})J^{T}(\boldsymbol{\eta})$, $\mathbf{B}=J^{-T}(\boldsymbol{\eta})\bar{\mathbf{B}}$.

III. CONTROLLER DESIGN

A. Common back-stepping controller designs

Firstly, defining the tracking error according to the thruster characteristic of the ship kinematic model as:

$$\bar{\mathbf{z}}_1=\mathbf{x}_1-\bar{\boldsymbol{\alpha}}_0 \tag{8}$$

$$\bar{\mathbf{z}}_2=\mathbf{x}_2-\bar{\boldsymbol{\alpha}}_1 \tag{9}$$

$$\bar{\mathbf{z}}_3=\mathbf{u}-\bar{\boldsymbol{\alpha}}_2 \tag{10}$$

where, $\bar{\boldsymbol{\alpha}}_0$ is the given position of $\mathbf{x}_{1d}$, $\bar{\boldsymbol{\alpha}}_1$ and $\bar{\boldsymbol{\alpha}}_2$ are the virtual controls of the back-stepping process.

Then, determining the derivation of every error vector one by one and considering the stability, the every virtual control is derived as:

$$\bar{\boldsymbol{\alpha}}_1=-\mathbf{k}_1\bar{\mathbf{z}}_1+\dot{\bar{\boldsymbol{\alpha}}}_0 \tag{11}$$

$$\bar{\boldsymbol{\alpha}}_2=\mathbf{M}_{\eta}(-\mathbf{k}_2\bar{\mathbf{z}}_2+\dot{\bar{\boldsymbol{\alpha}}}_1-\mathbf{f}(\mathbf{x}_1,\mathbf{x}_2)-\bar{\mathbf{z}}_1) \tag{12}$$

$$\bar{\boldsymbol{\alpha}}_3=\mathbf{B}^{-1}(-\mathbf{k}_3\mathbf{z}_3+\dot{\bar{\boldsymbol{\alpha}}}_2-\mathbf{A}\mathbf{u}-\mathbf{M}_{\eta}^{-T}\bar{\mathbf{z}}_2) \tag{13}$$

where,

$\mathbf{f}(\mathbf{x}_1,\mathbf{x}_2)=-\mathbf{M}_{\eta}^{-1}(\boldsymbol{\eta})[(\mathbf{C}_{\eta}(\mathbf{v},\boldsymbol{\eta})+\mathbf{D}_{\eta}(\mathbf{v},\boldsymbol{\eta}))\mathbf{x}_2+\mathbf{b}+\mathbf{J}\boldsymbol{\omega}]$, and $\mathbf{k}_i$ is the positive definite diagonal matrix, and $\boldsymbol{\tau}_e=\bar{\boldsymbol{\alpha}}_3$.

According to (10)-(13), this controller requires the system to meet the following assumptions:

Assumption 1: with all of the n-order system, the desired object $\boldsymbol{\alpha}_0$ has n-order derivation and the derivation of every order is continue and bounded.

Assumption 2: disturbing force is the given function and is derivable and bounded.

Assumption 3: ignoring the unmodeled dynamics on the model.

Notation: desired object $\boldsymbol{\alpha}_0$ is derived by designing reference system and its n-order derivation is existed only if the design is reasonable. The disturbing force and the unmodeled dynamics usually are derived by using disturbance observer or the intelligent algorism to compensate and estimate and handled by robust control mind.

Choosing the following Lyapunov function as

$$V_0=\frac{1}{2}\sum_{i=1}^{3}\bar{\mathbf{z}}_i^{T}\bar{\mathbf{z}}_i$$

And its derivation of time is

$$\dot{V}_0 = -\sum_{i=1}^{3} \bar{\mathbf{z}}_i^{\mathrm{T}} \mathbf{k}_i \bar{\mathbf{z}}_i \leq -\underline{\mathbf{k}} \sum_{i=1}^{3} \bar{\mathbf{z}}_i^{\mathrm{T}} \bar{\mathbf{z}}_i$$

where $\underline{\mathbf{k}} = \min\{\sigma_{\min}(\mathbf{k}_1), \sigma_{\min}(\mathbf{k}_2), \sigma_{\min}(\mathbf{k}_3)\}$. Therefore, the designed controller makes the tracking error system exponentially stable in the origin.

Though the aforementioned controller is simple in the form, the actual structure is complex because of the existence of the derivation of the virtual control. With the increasing of the system order, the derivation of the virtual control is becoming more and more complicated, and the requirements of system will increase. Therefore, this paper introduces the filter into the controller design and uses the 2-order filter to estimate the virtual control and the derivation. Thus, the derivation process in the conventional backstepping method is replaced by using filter. And this method greatly simplifies the controller design process and makes the form simple.

B. Filtering the backstepping controller design

The design step of filtering the backstepping controller is same to the conventional backstepping method, but the filter is designed to replace the derivation process of the virtual control. Thus, the assumption 1 is not necessary to set up and only meet the requirements of continue and bounded. And the tracking errors are similar to the abovementioned definition:

$$\mathbf{z}_1 = \mathbf{x}_1 - \mathbf{x}_{1c} \tag{14}$$

$$\mathbf{z}_2 = \mathbf{x}_2 - \mathbf{x}_{2c} \tag{15}$$

$$\mathbf{z}_3 = \mathbf{u} - \mathbf{x}_{3c} \tag{16}$$

where, $\mathbf{x}_{ic}(i = 1,2,3)$ is the output of the 2-order filter and is used to approach every virtual control. $\dot{\mathbf{x}}_{ic}(i = 1,2,3)$ is the derivation of $\mathbf{x}_{ic}(i = 1,2,3)$ and is the output of the 2-order filter.

Thus the expectation of every virtual control is

$$\boldsymbol{\alpha}_1 = -\mathbf{k}_1\mathbf{z}_1 + \dot{\mathbf{x}}_{1c} \tag{17}$$

$$\boldsymbol{\alpha}_2 = \mathbf{M}_\eta(-\mathbf{k}_2\mathbf{z}_2 + \dot{\mathbf{x}}_{2c} - \mathbf{f}(\mathbf{x}_1, \mathbf{x}_2) - \mathbf{v}_1) \tag{18}$$

$$\boldsymbol{\alpha}_3 = \mathbf{B}^{-1}(-\mathbf{k}_3\mathbf{z}_3 + \dot{\mathbf{x}}_{3c} - \mathbf{A}\mathbf{u} - \mathbf{M}_\eta^{-\mathrm{T}}\mathbf{v}_2) \tag{19}$$

where, the controller gain matrix $\mathbf{k}_i(i = 1,2,3)$ is accordance with the abovementioned; $\mathbf{v}_i$, $(i = 1,2,3)$ is the compensate vector of every tracking error and is defined as

$$\mathbf{v}_i = \mathbf{z}_i - \boldsymbol{\varsigma}_i \tag{20}$$

The vector $\boldsymbol{\varsigma}_i$ is defined as

$$\dot{\boldsymbol{\varsigma}}_i = -\mathbf{k}_i\boldsymbol{\varsigma}_i + \mathbf{g}_i(\mathrm{x}_{(i+1)\mathrm{c}} - \alpha_i) + \mathbf{g}_i\boldsymbol{\varsigma}_{i+1}, \ (i = 1,2) \tag{21}$$

where, $\mathbf{g}_1 = 1$, $\mathbf{g}_2 = \mathbf{M}_\eta^{-1}$, $\mathbf{g}_3 = \mathbf{B}$, and the initial value of $\boldsymbol{\varsigma}_i$ is zero ($\boldsymbol{\varsigma}_i(0) = \mathbf{0}$).

When $\boldsymbol{\varsigma}_3 = \mathbf{0}$, controller law is

$$\boldsymbol{\tau}_e = \boldsymbol{\alpha}_3 \tag{22}$$

$\mathbf{x}_{ic}$ and $\dot{\mathbf{x}}_{ic}$, $(i = 1,2,3)$ are needed in the controller design process. The following definitions are defined as

1) When $i = 1$, $\mathbf{x}_{1c} = \mathbf{x}_{1d} = \bar{\alpha}_0, \dot{\mathbf{x}}_{1c} = \dot{\mathbf{x}}_{1d} = \dot{\bar{\alpha}}_0$;

2) When $i = 2,3$, $\mathbf{x}_{ic}$ and $\dot{\mathbf{x}}_{ic}$ are output of the filter. The definition of every filter is defined as

$$\begin{aligned} \begin{bmatrix} \dot{\phi}_{i1} \\ \dot{\phi}_{i2} \end{bmatrix} &= \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\omega_{ni}^{\ 2}\mathbf{I} & -2\zeta_i\omega_{ni}\mathbf{I} \end{bmatrix} \begin{bmatrix} \phi_{i1} \\ \phi_{i2} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_{ni}^{\ 2}\mathbf{I} \end{bmatrix} \boldsymbol{\alpha}_{(i-1)\mathrm{c}} \\ \begin{bmatrix} \mathbf{x}_{ic} \\ \dot{\mathbf{x}}_{ic} \end{bmatrix} &= \begin{bmatrix} \phi_{i1} \\ \phi_{i2} \end{bmatrix} \end{aligned} \tag{23}$$

where, I is the three dimensional identity matrix. Obviously, $\mathbf{x}_{ic}$ and $\dot{\mathbf{x}}_{ic}$ is continue and bounded when $\boldsymbol{\alpha}_{(i-1)\mathrm{c}}$ is bounded.

IV. SIMULATION RESULTS

A computer simulation has been used to evaluate the performance of the command filtered backstepping controller. The parameters of the ship used to simulation is listed as follow :

$$\mathbf{M} = \begin{bmatrix} 9.1948 \cdot 10^7 & 0 & 0 \\ 0 & 9.1948 \cdot 10^7 & 1.2607 \cdot 10^9 \\ 0 & 1.2607 \cdot 10^9 & 1.0724 \cdot 10^{11} \end{bmatrix}$$

$$\mathbf{D}_l = \begin{bmatrix} 1.5073 \cdot 10^6 & 0 & 0 \\ 0 & 8.1687 \cdot 10^6 & -1.3180 \cdot 10^8 \\ 0 & -1.3180 \cdot 10^8 & 1.2568 \cdot 10^{11} \end{bmatrix}$$

$$\mathrm{D}_n(\mathbf{v}) = -\operatorname{diag}\{X_{|u|u} \mid u \mid, Y_{|v|v} \mid v \mid, N_{|r|r} \mid r \mid\}$$

where: $X_{|u|u} = -2.9766 \cdot 10^4$, $Y_{|v|v} = -8.0922 \cdot 10^4$, $N_{|r|r} = -1.2228 \cdot 10^{12}$.

The initial position and heading of the vessel is (0m, 0m, 0rad), and the initial velocity is (0m/s, 0m/s, 0rad/s). The desired position and heading is set as（2m, 1m, 5deg）. A straight reference path which make the ship in the process of uniform acceleration, uniform velocity and uniform deceleration motion to reach the desired position was generated by a reference model. In this simulation, the ship was designed to reach the target position in 200s.

The simulation results are shown in Figures 1-3. The solid lines are the results of command filtered backstepping controller and the dotted lines describe the results of traditional backstepping controller. Fig.1 shows that the tracking error of the two methods, which indicate the well tracking capability and Fig.2 describes the position and heading of the ship and the velocity of the ship. The control forces and moment of the ship are shown in Fig. 3.

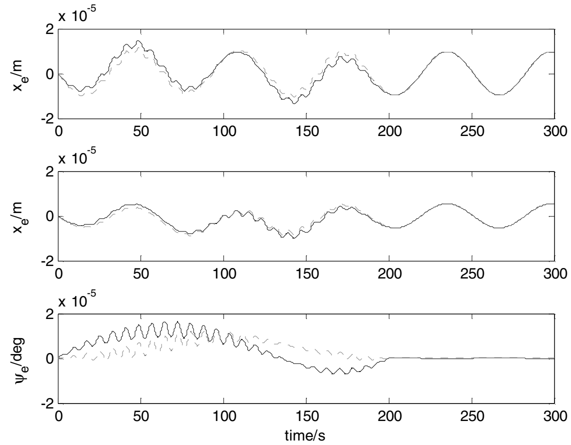

Fig. 1 the tracking error of the ship

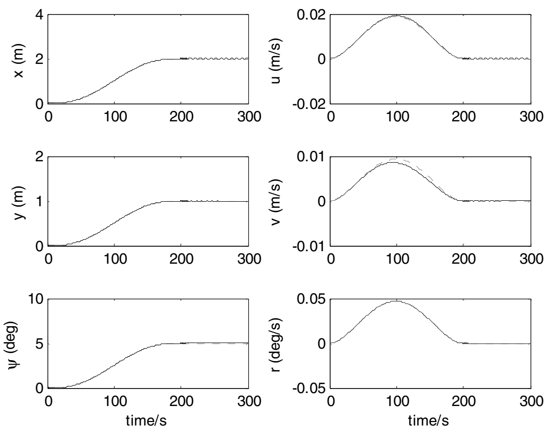

Fig. 3 the states of the ship

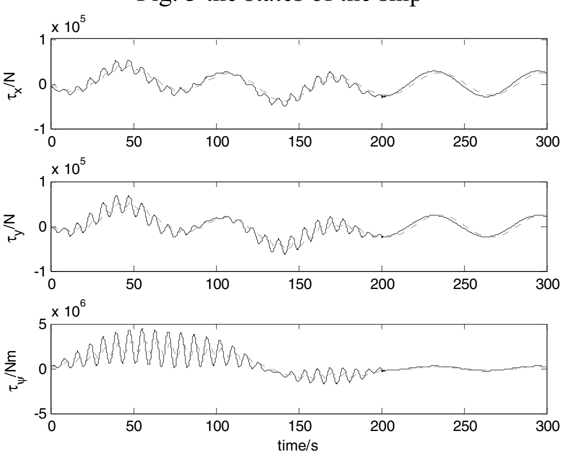

Fig. 3 the control forces and moment of the ship

V. CONCLUSIONS

In this paper, the mathematical model of a ship with thruster dynamics is established, with an adaptive filtered backstepping controller proposed. A second order filter is proposed to approximate the virtual control variables in order to avoid calculating their high order derivatives. Thus the design procedure is simplified, and the control law is much more concise. Meanwhile, the control forces are smooth enough to reduce the wear and tear of the actuators. Stability analysis and simulation results validate the effectiveness of the proposed controller.

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