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Finite-Time Trajectory Tracking for Marine Vessel by Nonsingular Backstepping Controller With Unknown External Disturbance

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ABSTRACT In this paper, a novel nonsingular finite-time backstepping controller is constructed for trajectory tracking of marine vessel subject to unknown external disturbances. Firstly, in the presence of disturbances, a disturbance observer (DO) is proposed to estimate and compensate the disturbances exactly in finite time. Secondly, a finite-time tracking controller is designed in the classical backstepping procedure, however, the inevitable singularity appears in calculating the derivative of virtual control. Furthermore, for overcoming this singularity, a nonsingular finite-time backstepping controller is designed by adopting a finite-time command filter to estimate the derivative, instead of calculating it directly. Theoretical analysis demonstrates the closed-loop system is finite-time stable. Finally, simulation results and comparisons illustrate the effectiveness of the proposed method.

INDEX TERMS Finite-time command filter, disturbance observer (DO), nonsingular finite-time backstepping controller, marine vessel, trajectory tracking.

I. INTRODUCTION

In the last decades, with the rapid development of marine exploration, the trajectory tracking problem of marine vessels has aroused more attention from both control engineering and marine technology communities. As water surface control is more complex than road surface, which is usually full of external disturbances (e.g., water currents) [1]. Simultaneously, the controlled marine vessel always has some unmodeled uncertainties, such as parameter's uncertainty, model calculation error etc. Therefore, it is necessary to design a robust trajectory tracking control scheme for rejecting the external disturbances and unmodeled uncertainties for marine vessels. Due to the remarkable features in stronger robustness and disturbance rejection properties, sliding mode control (SMC) has been applied to the motion control of marine vessels. References [2] and [3] adopt SMC to achieve tracking control of surface vessels. In [4], a new revised SMC law is presented for an underactuated surface vehicle (USV) with parameter uncertainties. Reference [5] proposes a trajectory tracking SMC law for autonomous underwater vehicles (AUVs) with conquering the quantization effect. However, since these prior methods include discontinuous term in SMC approach, so they will inevitably appear well-known chattering phenomenon when controlling the marine vessels. Subsequently, several new control methods appear, for instance, the adaptive control scheme [6] proposes a novel fixed-time output feedback control scheme for marine vessel tracking under unknown external disturbance and unmeasured velocity, the neural-network-based output feedback controllers [7]–[9] are proposed for the reference tracking for USV, and other intelligent control scheme [10]–[13] are also utilized to accomplish marine vessel tracking tasks. However, to the best of our knowledge, these methods mentioned above either exist the chattering control or need a complex designing procedure, which are difficult to use in practice.

In recent years, the nonlinear backstepping control technique is proved with its effectiveness and designing simplicity to use for controlling the marine vessels. In [14] and [15], a disturbance observer is used to estimate unknown external disturbance, then combining backstepping method to accomplish trajectory tracking. Reference [16] combines adaptive feedback approximation technique and

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backstepping to design an adaptive neutral network control. Reference [17] proposes a state feedback fault-tolerant adaptive backstepping controller to track desired trajectory with unknown disturbance. But it is inevitable to calculate the derivation of virtual control in the backstepping methods above. The computational processes are complicated, and it may easily cause "explosion of complexity" problem [18]. To overcome the problems above, the dynamic surface control (DSC) is introduced firstly in [19]. In [20], it also uses a first order filter to reach AUV path following. By designing a first order filter, let virtual control pass through it as input signal, then the output is the estimation of virtual control and its derivation. It should be mentioned that the filtering error is neglected. So, it will influence the control performance. To eliminate the error, [21] proposes the command filtered control firstly and is successfully used, which constructs an error compensation mechanism to compensate filter error [22]–[24]. References [23], [25], [26], using a finite-time command filter based on Levant's differentiator, combining with error compensation mechanism, can quickly filter virtual control and obtain its differential signals for nonlinear system and robotic manipulator system. However, on the surface of the water, the prior conventional backstepping methods can not satisfy the finite-time tracking control with the time-varying disturbances. In general, the tracking control of marine vessels not only needs a theoretically high tracking precision, but also requires both the fast finite-time convergence [27] and strong disturbance rejection ability [28], [29].

For the fast finite-time convergence, terminal sliding mode control (TSMC) is one of commonly used methods. For instances, [30] and [31] achieve the tracking control of rigid robotic manipulators in finite time. But the traditional TSMC may occur singular phenomenon [31], so [29] proposes a nonsingular TSMC. It can avoid the problem effectively. A continuous finite-time control scheme for rigid robotic manipulators is proposed using a new form of terminal sliding modes [32]. In [30], it develops a nonsingular SMC scheme combining with finite-time disturbance observer to accomplish marine vessel tracking in finite time. In [29], a continuous higher order finite-time controller based on sampled-data is proposed for the trajectory tracking. In [33], an adaptive backstepping fuzzy neural network fractional-order control using a nonsingular TSMC is proposed for the microgyroscope. In [34], an adaptive fuzzy-neural fractional-order current control with finite-time SMC is used for the active power filter. In [35]–[37], the combination of neural network (NN) and SMC are used to control the complex system for the fast finite-time convergence.

For the strong disturbance rejection ability, the disturbance observer is the most common technique cooperated with the trajectory tracking controller for marine vessels. Such as exponential disturbance observer [14], [38], finite-time disturbance observers [6], [39], finite-time extended state observer [40], fixed-time extended state observer [6], [24], TSMC disturbance observer [41], and adaptive disturbance observer [42], [43]. In [44], the disturbance observer based fuzzy SMC is used as a robust way of disturbance rejection. In [42], the active disturbance rejection adaptive control is introduced in detail for the uncertain nonlinear systems. In [43], the disturbance observer can be transformed to be an output feedback approach for the time-varying input delay compensation of the nonlinear systems with additive disturbance. And NN scheme [45] is also used to approximate the external disturbance and model uncertainties. Since the estimation capacity of disturbance observer will affect control performance directly. So, it is vital to construct a disturbance observer of high performance.

According to the researches above, the traditional backstepping technique aforementioned only can guarantee the tracking error converge to a bounded region, in generally, which may not accomplish zero error tracking in finite time. So, we present a novel nonsingular finite-time backstepping controller combining with a finite-time disturbance observer in this paper. The main contributions are reflected as follows:

(1) A finite-time disturbance observer (FTDO) is constructed inspired by [28] and [41]. Compared with discontinuous disturbance observer in [41], the proposed FTDO is continuous, so it can avoid chattering phenomenon. And it can estimate unknown disturbance within finite time.

(2) The traditional backstepping approaches [14], [15] can only achieve the uniformly ultimately bounded convergence, i.e., the tracking error only converges to a region. However, the proposed finite-time backstepping controller can accomplish zero error tracking in finite time, which adopts a finite-time command filter based on the first-order Levant differentiator to obtain virtual control's derivative. It can not only greatly reduce the computational complexities compared with the traditional backstepping approaches, but also avoid singular phenomenon effectively.

This paper is organized as follows. The problem formulation and preliminaries are presented in section 2. In section 3, the design of disturbance observer is presented. In section 4, the singular and nonsingular finite-time backstepping controllers are developed respectively to achieve the trajectory tracking for marine vessel, and their stabilities are proved. In section 5, the algorithm structure of the proposed control scheme is given. In section 6, the comparison simulations are illustrated. And finally, we conclude this paper and propose some future works in Section 7.

II. PROBLEM FORMULATION

This paper aims at constructing a DO to provide estimation of external disturbance firstly, and then developing a novel nonsingular finite-time backstepping controller to achieve trajectory tracking within finite time when marine vessel is affected by unknown time-varying disturbances satisfying Assumption 1.

A. PRELIMINARIES

The two reference coordinate frames of ship motion are defined commonly as Fig.1. For marine vessels, the

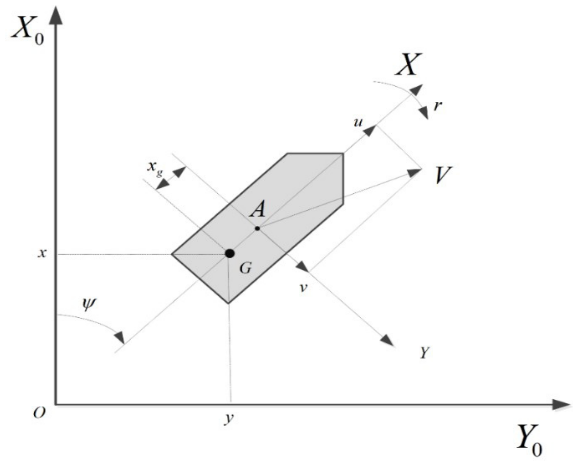

FIGURE 1. Earth-fixed and body-fixed frame.

mathematical model in 3-DOF is described as follow:

$$\begin{cases} \dot{\eta} = R(\psi)v \\ M\dot{v} + C(v)v + D(v)v = \tau + d \end{cases} \tag{1}$$

where $\eta = [x, y, \psi]^T$ denotes the north position, east position and heading angle of marine surface vessel in the earth-fixed inertial frame; $v = [u, v, r]^T$ denotes surge velocity, sway velocity, and yaw velocity in the body-fixed reference frame. $R(\psi)$ is a transformation matrix between earth-fixed and body-fixed reference frame, i.e., $R(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$ and with the follow properties:

$$\dot{R}(\psi) = R(\psi)S(r),$$
$$R^T(\psi)S(r)R(\psi) = R(\psi)S(r)R^T(\psi) = S(r),$$
$$S(r) = \begin{bmatrix} 0 & -r & 0 \\ r & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$
$$R^T(\psi)R(\psi) = I \quad and \ ||R(\psi)|| = 1,$$

$M \in R^{3\times3}$, $C(v) \in R^{3\times3}$, and $D(v) \in R^{3\times3}$ denote the inertial mass matrix, Coriolis matrix and hydrodynamic damping matrix, respectively. $\tau = [\tau_1, \tau_2, \tau_3]^T$ is the control input, $d = [d_1, d_2, d_3]^T$ is the lumped disturbances including the unknown external disturbances and the unknown unmodeled uncertainties.

Assumption 1: The lumped disturbance d is unknown time-varying but bounded, and there exists a positive constant d_M satisfying $\|\dot{d}\|_\infty \leq d_M$.

Lemma 1 [2]: An extended Lyapunov description of finite-time stability can be given as:

$$\dot{V}(x) + \alpha V(x) + \beta V^\gamma(x) \leq 0, \quad 0 < \gamma < 1 \tag{2}$$

and the setting time can be given by $T \leq \frac{1}{\alpha(1-\gamma)} \ln \frac{\alpha V^{1-\gamma}(x_0)+\beta}{\beta}$.

Lemma 2 [26]: For all $x_i \in R$ $(i = 1, 2 \ldots\ldots n)$, and $0 < p \leq 1$, then

$$(\sum_{i=1}^{n} |x_i|)^p \leq \sum_{i=1}^{n} |x_i|^p \leq n^{1-p}(\sum_{i=1}^{n} |x_i|)^p \tag{3}$$

Lemma 3 [26]: Consider the following first-order Levant differentiator:

$$\begin{cases} \dot{\beta}_1 = z \\ z = -l_1|\beta_1 - \alpha|^{\frac{1}{2}} sign(\beta_1 - \alpha) + \beta_2 \\ \dot{\beta}_2 = -l_2 sign(\beta_2 - z) \end{cases} \tag{4}$$

where α is an input signal, l_1 and l_2 are positive constants. If the parameters are selected properly, and in the absence of noise, the following equalities hold:

$$\beta_1 = \alpha, \quad z = \dot{\alpha} \tag{5}$$

Lemma 4 [28]: Let the input noise satisfy the inequality $|\alpha - \alpha_0| < \epsilon$, then the following inequalities are established in finite time by some positive constants μ_1, ν_1 depending exclusively on the parameters of differentiator:

$$\begin{cases} |\beta_1 - \alpha_0| \leq \mu_1\kappa < \varrho_1 \\ \lceil \dot{\beta}_1 - \dot{\alpha}_0 \rceil \leq \nu_1\kappa^{\frac{1}{2}} < \varrho_2 \end{cases} \tag{6}$$

Lemma 5 [28], [46]: The following system:

$$\begin{cases} \dot{x}_1 = -k_1 sig^{\frac{1}{2}}(x_1) + x_2 \\ \dot{x}_2 = -k_2 sgn(x_1) + L \end{cases} \tag{7}$$

where $|L| \leq L_M$, L_M is a positive constant, k_1 and k_2 are both positive constants, the system is finite-time stable, $sig^{\frac{1}{2}}(x_1)$ and $sgn(x_1)$ are defined as following notations [6]:

$\lambda_{\min}\{\cdot\}$ and $\lambda_{\max}\{\cdot\}$ are defined respectively as the minimum and maximum eigenvalue of a matrix $\{\cdot\}$.

(1) Define $x = \{x_1, x_2, \cdots x_n\}^T \in R^n$, $sig^\alpha(x) = [sig^\alpha(x_1), sig^\alpha(x_2), sig^\alpha(x_3)]^T$, where $sig^\alpha(x) = sgn(x_i)|x_i|^\alpha$ $(i = 1, 2, \cdots n)$, $x_i \in R$, $\alpha \in (0, 1)$. $sgn(\cdot)$ is a sign function given by

$$sgn(x) = \begin{cases} -1, & if \ x < 0 \\ 0, & if \ x = 0 \\ 1, & if \ x > 0 \end{cases} \tag{8}$$

(2) $diag(x_1, x_2, x_3)$ denotes a diagonal matrix, where x_1, x_2 and x_3 are its elements respectively.

(3) When $x \in R^3$, the vector $x = [x_1, x_2, x_3]^T$. When $x_i \in R^3$, the vector $x_i = [x_{i1}, x_{i2}, x_{i3}]^T$.

III. DISTURBANCE OBSERVER DESIGN

For the purpose of estimating the unknown external disturbance, the DO is constructed as follows.

The new variable is introduced firstly:

$$\Pi = Mv - M\chi \tag{9}$$

The derivative of χ is designed as follows:

$$\dot{\chi} = M^{-1}[\tau - Cv - Dv + \kappa_1 sig^{\frac{1}{2}}(\Pi) + \int_0^t \kappa_2 sign(\Pi)dt] \tag{10}$$

where κ_1 and κ_2 are both positive constants, and the estimation of disturbance is designed as:

$$\hat{d} = \int_0^t \kappa_2 sign(\Pi)dt \tag{11}$$

Theorem 1: Under the Assumption 1, the disturbance observer (9), (10) and (11) can precisely estimate the unknown external disturbance in finite time when selecting the proper parameters κ_1 and κ_2.

Proof: According to (9), the derivative of Π can obtain:

$$\dot{\Pi} = M\dot{v} - M\dot{\chi} = -\kappa_1 sig^{\frac{1}{2}}(\Pi) - \int_0^t \kappa_2 sign(\Pi)dt + d \tag{12}$$

Let $\rho = -\int_0^t \kappa_2 sign(\Pi)dt + d$, then (12) can be written as:

$$\begin{cases} \dot{\Pi} = -\kappa_1 sig^{\frac{1}{2}}(\Pi) + \rho \\ \dot{\rho} = -\kappa_2 sign(\Pi) + \dot{d} \end{cases} \tag{13}$$

By Lemma 5, we can obtain $\Pi = 0$ and $\rho = 0$ in finite time t_d.

Then, we can obtain $\rho = d - \int_0^t \kappa_2 sign(\Pi)dt = d - \hat{d} = 0$ after finite time t_d. So, the unknown disturbance can be estimated by $\hat{d}$ precisely in finite time.

IV. CONTROLLER DESIGN AND STABILITY ANALYSIS

In this section, we will design a finite-time vessel trajectory tracking controller firstly. Next, in order to avoid the singularity problem, we design a nonsingular finite-time trajectory tracking controller.

A. FINITE-TIME TRAJECTORY TRACKING CONTROLLER

Step 1:

We define a position error vector $z_1 \in R^3$ as:

$$z_1 = \eta - \eta_d \tag{14}$$

where η_d is desired trajectory.

Next, we design a virtual control $\alpha \in R^3$ as:

$$\alpha = R^T(-k_1 z_1 + \dot{\eta}_d - s_1|z_1|^{\gamma} sign(z_1)) \tag{15}$$

where $|z_1|^{\gamma} sign(z_1) = [z_{11}^{\gamma} \cdot sign(z_{11}) \quad z_{12}^{\gamma} \cdot sign(z_{12}) \quad z_{13}^{\gamma} \cdot sign(z_{13})]^T$, s_1 is a positive constant, k_1 is a positive definite matrix.

Define a Lyapunov function:

$$V_1 = \frac{1}{2} z_1^T z_1 \tag{16}$$

And its derivative with respect to time is:

$$\dot{V}_1 = z_1^T \dot{z}_1 = z_1^T(\dot{\eta} - \dot{\eta}_d) = z_1^T(Rv - \dot{\eta}_d) \tag{17}$$

Step 2:

Then, define a velocity error vector $z_2 \in R^3$ as:

$$z_2 = v - \alpha \tag{18}$$

According (15) and (18), then (17) can be rewritten as:

$$\begin{aligned} \dot{V}_1 &= z_1^T \dot{z}_1 \\ &= z_1^T(Rz_2 + R\alpha - \dot{\eta}_d) \\ &= z_1^T(Rz_2 - k_1 z_1 + \dot{\eta}_d - s_1|z_1|^{\gamma} sign(z_1) - \dot{\eta}_d) \\ &= z_1^T(Rz_2 - k_1 z_1 - s_1|z_1|^{\gamma} sign(z_1)) \end{aligned} \tag{19}$$

According to (1) and (18), we can obtain:

$$M\dot{z}_2 = M(\dot{v} - \dot{\alpha}) = \tau - (C + D)v + d - M\dot{\alpha} \tag{20}$$

Define a Lyapunov function:

$$V_2 = V_1 + \frac{1}{2} z_2^T M z_2 \tag{21}$$

From (19) and (20), taking the derivative of V_2 yields

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + z_2^T M \dot{z}_2 \\ &= z_1^T(Rz_2 - k_1 z_1 - s_1|z_1|^{\gamma} sign(z_1)) \\ &\quad + z_2^T(\tau - (C + D)v + d - M\dot{\alpha}) \end{aligned} \tag{22}$$

We design the control law as follows:

$$\tau = (C + D)v + M\dot{\alpha} - R^T z_1 - k_2 z_2 - \hat{d} - s_2|z_2|^{\gamma} sign(z_2) \tag{23}$$

where the form of $|z_2|^{\gamma} sign(z_2)$ is similar to (15), s_2 is a positive constant, k_2 is a positive definite matrix. From (3) and (23), then

$$\begin{aligned} \dot{V}_2 &= z_1^T(Rz_2 - k_1 z_1 - s_1|z_1|^{\gamma} sign(z_1)) \\ &\quad + z_2^T(-R^T z_1 - k_2 z_2 - s_2|z_2|^{\gamma} sign(z_2) + d - \hat{d}) \\ &= -z_1^T k_1 z_1 - z_2^T k_2 z_2 - z_1^T s_1|z_1|^{\gamma} sign(z_1) \\ &\quad - z_2^T s_2|z_2|^{\gamma} sign(z_2) + d - \hat{d} \\ &\leq -z_1^T k_1 z_1 - z_2^T k_2 z_2 - s_1(z_1^T z_1)^{\frac{\gamma+1}{2}} - s_2(z_2^T z_2)^{\frac{\gamma+1}{2}} \\ &\quad + \frac{1}{2} z_2^T z_2 + \frac{1}{2}(\hat{d} - d)^T(\hat{d} - d) \\ &\leq -\mu_0 V - \mu_1 V^{\frac{\gamma+1}{2}} + c \end{aligned} \tag{24}$$

where $\mu_0 = \min\{\lambda_{\min}(2k_1), \lambda_{\min}(2k_2) - 1\}$, $\mu_1 = \min\{s_1, s_2\}$, $c = \frac{1}{2}(\hat{d} - d)^T(\hat{d} - d)$.

When $t \leq t_d$, from Section A, defining e as disturbance estimation error, we can obtain $e = d - \hat{d} = d - \int_0^{t_1} \kappa_2 sign(\Pi)dt$. The d is bounded, and $sign(\Pi)$ is a bounded function, so the e is bounded, and it satisfies $c = \frac{1}{2} e^T e \leq \Omega$, when $t \leq t_d$, where Ω is a positive constant. So it can not escape into infinite region when $t \leq t_d$.

When $t \geq t_d$, $c = 0$, according Lemma 1, V_2 is finite-time stable after t_s, so z_1 converges to zero in finite time $T_s = t_d + t_s$.

However, we can see that it is necessary to compute the derivative of virtual control α in the control law's designing. When computing virtual law's derivative, it will appear the term of $|z_1|^{\gamma-1}\dot{z}_1$ in control force, so it is singular when $z_1 = 0, \dot{z}_1 \neq 0$. In order to avoid the singularity problem, we will design a nonsingular controller in the next section.

B. NONSINGULAR FINITE-TIME TRAJECTORY TRACKING CONTROLLER

In this section, we present the nonsingular finite-time trajectory tracking controller to accomplish control task by introducing a finite-time command filter.

Step1:

We define a position error vector $z_1 \in R^3$ as:

$$z_1 = \eta - \eta_d \tag{25}$$

where η_d is desired trajectory.

Next, we design a virtual control $\alpha \in R^3$ as:

$$\alpha = R^T(-k_1 z_1 + \dot{\eta}_d - s_1|\omega_1|^{\gamma} sign(\omega_1)) \tag{26}$$

where $|\omega_1|^{\gamma} sign(\omega_1) = [\omega_{11}^{\gamma} \cdot sign(\omega_{11}) \quad \omega_{12}^{\gamma} \cdot sign(\omega_{12}) \quad \omega_{13}^{\gamma} \cdot sign(\omega_{13})]^T$, k_1 is a positive definite matrix, s_1 and γ_1 are positive constants, and $0 < \gamma_1 < 1$, ω_1 will be designed later.

In order to avoid computing the virtual control law's derivative. So, we introduce a finite-time command filter by Lemma 3 as follow:

$$\begin{cases} \dot{\beta} = z \\ z = -l_1|\beta - \alpha|^{\frac{1}{2}} sign(\beta - \alpha) + w \\ \dot{w} = -l_2 sign(w - z) \end{cases} \tag{27}$$

where $A = diag(|\beta_1 - \alpha_1|^{\frac{1}{2}}, |\beta_2 - \alpha_2|^{\frac{1}{2}}, |\beta_3 - \alpha_3|^{\frac{1}{2}})$, α is an input vector, the finite-time command filter's output β and $\dot{\beta}$ are utilized to estimate α and its derivative.

However, the filter error $\beta - \alpha$ is omitted in traditional DSC technique, in order to obtain more accurate filter signal, introducing a filter error compensation mechanism inspired by [21] and [22]

$$\dot{\xi}_1 = -k_1\xi_1 + R(\beta - \alpha) + R\xi_2 - \rho_1 sign(\xi_1) \tag{28}$$

where ξ_2 will be designed later.

Define a compensation tracking error vector $\omega_1 \in R^3$ as:

$$\omega_1 = z_1 - \xi_1 \tag{29}$$

Then, the Lyapunov function is constructed as:

$$V_1 = \frac{1}{2}\omega_1^T\omega_1 \tag{30}$$

And its derivative with respect to time is:

$$\dot{V}_1 = \omega_1^T\dot{\omega}_1 = \omega_1^T(\dot{z}_1 - \dot{\xi}_1) = \omega_1^T(\dot{\eta} - \dot{\eta}_d - \dot{\xi}_1) \tag{31}$$

According to (1) and (28), we have

$$\dot{V}_1 = \omega_1^T(Rv - \dot{\eta}_d + k_1\xi_1 - R(\beta - \alpha) - R\xi_2 + \rho_1 sign(\xi_1)) \tag{32}$$

Step2:

Define

$$\dot{\xi}_2 = M^{-1}(-k_2\xi_2 - R\xi_1 - \rho_2 sign(\xi_2)) \tag{33}$$

And a velocity error vector $z_2 \in R^3$ as:

$$z_2 = v - \beta \tag{34}$$

Define the compensation tracking error vector $\omega_2 \in R^3$ as:

$$\omega_2 = z_2 - \xi_2 \tag{35}$$

According to (26), (34) and (35), then (32) can be rewritten as:

$$\begin{aligned} \dot{V}_1 &= \omega_1^T[Rz_2 + R(\beta - \alpha) + R\alpha - \dot{\eta}_d + k_1\xi_1 - R(\beta - \alpha) \\ &\quad - R\xi_2 + \rho_1 sign(\xi_1)] \\ &= \omega_1^T[Rz_2 - k_1 z_1 + \dot{\eta}_d - s_1|\omega_1|^{\gamma} sign(\omega_1) - \dot{\eta}_d \\ &\quad + k_1\xi_1 - R\xi_2 + \rho_1 sign(\xi_1)] \\ &= \omega_1^T[R\omega_2 - k_1\omega_1 - s_1|\omega_1|^{\gamma} sign(\omega_1) + \rho_1 sign(\xi_1)] \end{aligned} \tag{36}$$

By (1), (33), (34) and (35), we have

$$\begin{aligned} &M\dot{\omega}_2 \\ &= M(\dot{z}_2 - \dot{\xi}_2) = M(\dot{v} - \dot{\beta} - \dot{\xi}_2) \\ &= \tau - (C + D)v + d - M(\dot{\beta} + \dot{\xi}_2) \\ &= \tau - (C + D)v + d - M\dot{\beta} + k_2\xi_2 + R\xi_1 + \rho_2 sign(\xi_2) \end{aligned} \tag{37}$$

Then, we design the marine vessel trajectory tracking control law as below:

$$\begin{aligned} \tau = (C + D)v + M\dot{\beta} - R^T\omega_1 - k_2 z_2 - d \\ - s_2|\omega_2|^{\gamma} sign(\omega_2) \end{aligned} \tag{38}$$

where $|\omega_2|^{\gamma} sign(\omega_2) = [\omega_{21}^{\gamma} \cdot sign(\omega_{21}) \quad \omega_{22}^{\gamma} \cdot sign(\omega_{22}) \quad \omega_{23}^{\gamma} \cdot sign(\omega_{23})]^T$, k_2 is a positive definite matrix, s_2 and γ_2 are positive constant, and $0 < \gamma_2 < 1$.

Theorem 2: Consider the marine vessel model (1) in the presence of unknown time-varying disturbances $d(t)$. Under the Assumption 1, marine vessel trajectory tracking control law (38), and finite-time command filter (27), the tracking error will converge to zero in finite time $t \geq max\{T_n, T_1\}$, where T_n and T_1 are given by the following proof. The parameters of (26) and (38) are chosen as: $s_1 > 0, s_2 > 0$, $\lambda_{\min}(2k_1) > 0$, $\lambda_{\min}(2k_2) - 1 > 0$, $k_1 > 0$, $\lambda_{\min}(2k_2M^{-1}) > 0$, and $\rho_1 > 0$, $(2M^{-1})^{\frac{1}{2}}\rho_2 > 0$.

Proof: Define a Lyapunov function:

$$V_2 = V_1 + \frac{1}{2}\omega_2^T M\omega_2 \tag{39}$$

By (36), (37) and (38), taking the derivative of V_2 yields

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + \omega_2^T M\dot{\omega}_2 \\ &= \omega_1^T(R\omega_2 - k_1\omega_1 + \rho_1 sign(\xi_1) - s_1|\omega_1|^{\gamma} sign(\omega_1)) \\ &\quad + \omega_2^T(\tau - (C + D)v + d - M\dot{\beta} + k_2\xi_2 \\ &\quad + R\xi_1 + \rho_2 sign(\xi_2)) \end{aligned}$$

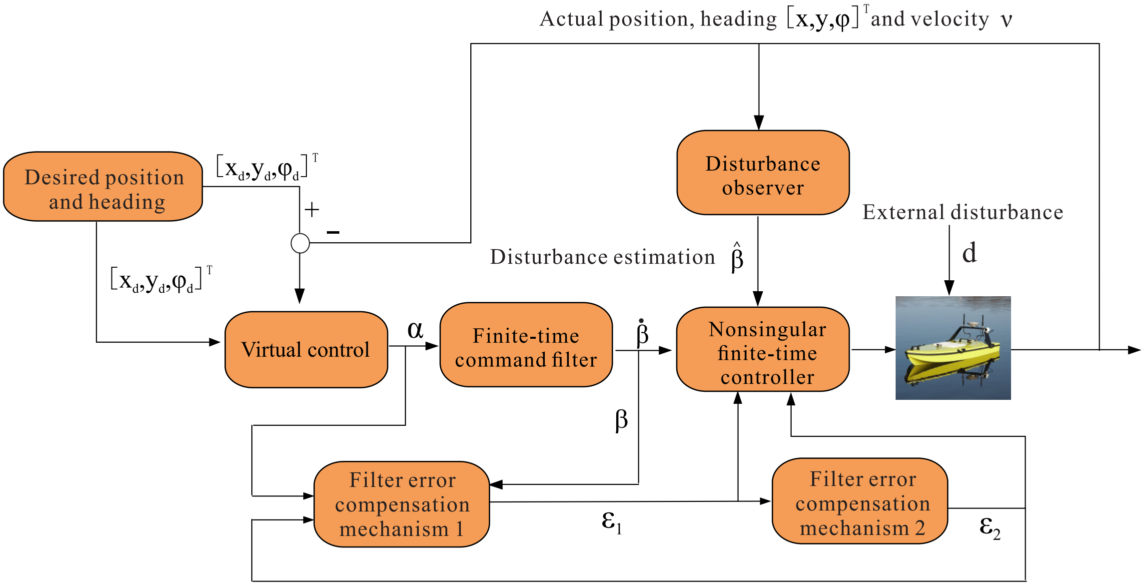

FIGURE 2. **The algorithm structure of the proposed control scheme.**

$$
\begin{aligned}
&= -\omega_1^T k_1\omega_1 + \omega_1^T \rho_1 sign(\xi_1) \\
&\quad - s_1\omega_1^T(|\omega_1|^\gamma sign(\omega_1)) - \omega_2^T k_2\omega_2 \\
&\quad - s_2\omega_2^T(|\omega_2|^\gamma sign(\omega_2)) + \omega_2^T \rho_2 sign(\xi_2) + \omega_2^T(d-d)
\end{aligned} \tag{40}
$$

By Lemma 2 and Young's inequality, it yields:

$$
\begin{aligned}
\dot{V}_2 &\le -\omega_1^T k_1\omega_1 - s_1(\omega_1^T\omega_1)^{\frac{\gamma+1}{2}} - \omega_2^T k_2\omega_2 \\
&\quad - s_2(\omega_2^T\omega_2)^{\frac{\gamma+1}{2}} + \frac{\rho_1\omega_1^T\omega_1}{2} + \frac{\rho_2\omega_2^T\omega_2}{2} \\
&\quad + \frac{1}{2}z_2^T z_2 + \frac{\rho_1 sign(\xi_1)^T sign(\xi_1)}{2} \\
&\quad + \frac{\rho_2 sign(\xi_2)^T sign(\xi_2)}{2} + \frac{1}{2}(\hat{d}-d)^T(\hat{d}-d) \\
&\le -\mu_2 V - \mu_3 V^{\frac{\gamma+1}{2}} + c_1
\end{aligned} \tag{41}
$$

where $\mu_2 = \min\{\lambda_{\min}(2k_1), \lambda_{\min}(2k_2)-1\}$, $\mu_3 = \min\{s_1, s_2\}$, $c_1 = \frac{\rho_1 sign(\xi_1)^T sign(\xi_1)}{2} + \frac{\rho_2 sign(\xi_2)^T sign(\xi_2)}{2} + \frac{1}{2}(d-d)^T(d-d)$. Then, we can obtain $\frac{\rho_1 sign(\xi_1)^T sign(\xi_1)}{2} + \frac{\rho_2 sign(\xi_2)^T sign(\xi_2)}{2} \le \frac{3\rho_1}{2} + \frac{3\rho_2}{2}$ if $t \le t_d$ and $c_1 \le \frac{3\rho_1}{2} + \frac{3\rho_2}{2} + \Omega$, where the Ω is defined in Section A. So it can not escape into infinite region when $t \le t_d$. Meanwhile, if $t > t_d$, $d - d = 0$, so $c_1 = \frac{\rho_1 sign(\xi_1)^T sign(\xi_1)}{2} + \frac{\rho_2 sign(\xi_2)^T sign(\xi_2)}{2} \le \frac{3\rho_1}{2} + \frac{3\rho_2}{2} = \gamma$. Then, (41) can be written as:

$$
\dot{V}_2 \le -\mu_2 V_2 - \mu_3 V_2^{\frac{\gamma+1}{2}} + \gamma \tag{42}
$$

Furthermore, according to [26], the compensation tracking error $\|\omega_1\|$ will converge to the region of $max\{\sqrt{\frac{\gamma}{\mu_0}}, \sqrt{2(\frac{\gamma}{2\mu_0})^{\frac{2}{\lambda+1}}}\}$ in finite time $T_n = t_d + t_n$, where t_n is the time that $\|\omega_1\|$ reaches the region after t_d. And the parameters are chosen as: $s_1 > 0$, $s_2 > 0$, $\lambda_{\min}(2k_1) > 0$, and $\lambda_{\min}(2k_2) - 1 > 0$.

We construct a Lyapunov function about ξ_i $(i = 1, 2)$,

$$
V_\xi = \frac{1}{2}\xi_1^T\xi_1 + \frac{1}{2}\xi_2^T M\xi_2 \tag{43}
$$

Its derivative can be written as

$$
\begin{aligned}
\dot{V}_\xi &= \xi_1^T\dot{\xi}_1 + \xi_2^T\dot{\xi}_2 \\
&= -\xi_1^T k_1\xi_1 - \xi_2^T k_2\xi_2 + \xi_1^T R(\beta-\alpha) \\
&\quad - \xi_1^T \rho_1 sign(\xi_1) - \xi_2^T \rho_2 sign(\xi_2)
\end{aligned} \tag{44}
$$

By (6), $0 \le |\beta - \alpha| \le \varrho$ can be achieved in finite time t_f, where ϱ is a nonnegative constant. Let $f = |R||\beta-\alpha|$, and the f be written as $f = [f_1, f_2, f_3]^T$. If the elements of matrix R is bounded, so the f is bounded, and it satisfies $f < \chi$, where χ is a positive constant. Then, according to Lemma 2, we have

$$
\begin{aligned}
\dot{V}_\xi &\le -\min\{\lambda_{\min}(2k_1), \lambda_{\min}(2k_2M^{-1})\}(\frac{1}{2}\xi_1^T\xi_1 + \frac{1}{2}\xi_2^T M\xi_2) \\
&\quad - \sqrt{2}min\{(\rho_1 - f_1), (\rho_1 - f_2), (\rho_1 - f_3)\}(\frac{1}{2}\xi_1^T\xi_1)^{\frac{1}{2}} \\
&\quad - (2\lambda_{\min}(M^{-1}))^{\frac{1}{2}}\rho_2(\frac{1}{2}\xi_2^T M\xi_2)^{\frac{1}{2}} \\
&\le -\kappa_0 V_\xi - \kappa_1 V_\xi^{\frac{1}{2}}
\end{aligned} \tag{45}
$$

where the parameters are selected as $\kappa_0 = \min\{\lambda_{\min}(2k_1), \lambda_{\min}(2k_2M^{-1})\}$, $\kappa_1 = \sqrt{2}\min\{(\rho_1 - f_1), (\rho_1 - f_2), (\rho_1 - f_3)\}$, $(2\lambda_{\min}(M^{-1}))^{\frac{1}{2}}\rho_2 > 0$, $\lambda_{\min}(2k_1) > 0$, $\lambda_{\min}(2k_2M^{-1}) > 0$, and $\rho_1 - f_1 > 0$, $\rho_1 - f_2 > 0$, $\rho_1 - f_3 > 0$, $(2M^{-1})^{\frac{1}{2}}\rho_2 > 0$.

Overall, we can obtain $\beta - \alpha = 0$ from (5) in the absence of noise, then $f = 0$, so the parameters are selected as $\lambda_{\min}(2k_1) > 0$, $\lambda_{\min}(2k_2M^{-1}) > 0$, and $\rho_1 > 0$, $(2M^{-1})^{\frac{1}{2}}\rho_2 > 0$. By Lemma 2 and (45), we can have $\xi_i = 0$ $(i = 1, 2)$ after $t_\xi = \frac{2}{\kappa_0}\ln(\frac{\kappa_0 V^{\frac{1}{2}} + \kappa_1}{\kappa_1})$, i.e., $c_1 = \gamma = 0$. Then, according to (42) and Lemma 1, ω_1 converges to zero in finite

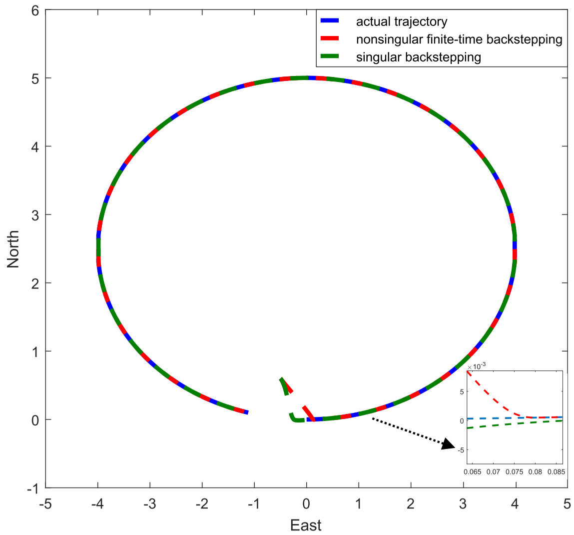

FIGURE 3. The trajectory under the singular and the nonsingular finite-time backstepping.

time T, when $T \geq max\{T_n, T_1\}$, where $T_1 = t_f + t_\xi$, so we can conclude that z_1 also converges to zero in finite time T from (29). Theorem 1 is thus proved.

V. THE ALGORITHM STRUCTURE OF THE PROPOSED CONTROL SCHEME

In Fig. 2, the detailed block diagram of the proposed approach is shown. The novel nonsingular finite-time backstepping controller is constructed for trajectory tracking of marine vessel subject to unknown external disturbances. A finite-time command filter is used to estimate the derivative of virtual control. The proposed FTDO is used to estimate and compensate the disturbances exactly in finite time.

VI. SIMULATION STUDIES

In this section, simulation results are presented to illustrate the efficiency of the proposed control algorithm. And the marine vessel model is selected as Cyber Ship II. Its model parameter inertia matrix M, Coriolis matrix C, and the nonlinear damping matrix D are selected as

$$M = \begin{bmatrix} 25.8 & 0 & 0 \\ 0 & 33.8 & 1.015 \\ 0 & 1.0015 & 2.76 \end{bmatrix},$$

$$C = \begin{bmatrix} 0 & 0 & -33.8v - 1.0115r \\ 0 & 0 & 25.8u \\ 33.8v + 1.0115r & -25.8u & 0 \end{bmatrix},$$

$$D = \begin{bmatrix} 0.72 + 1.33|u| + 5.87u^2 & 0 & 0 \\ 0 & 0.8896+36.5|v|+0.805|r| & 7.25 + 0.845|v| + 3.45|r| \\ 0 & 0.0313+3.96|v|-0.130|r| & 1.90 - 0.080|v| + 0.75|r| \end{bmatrix}.$$

In this simulation, we assume that marine vessel's initial states are $\eta(0) = [-0.5, 0.6, pi/4]$, $v(0) = [0, 0, 0]$.

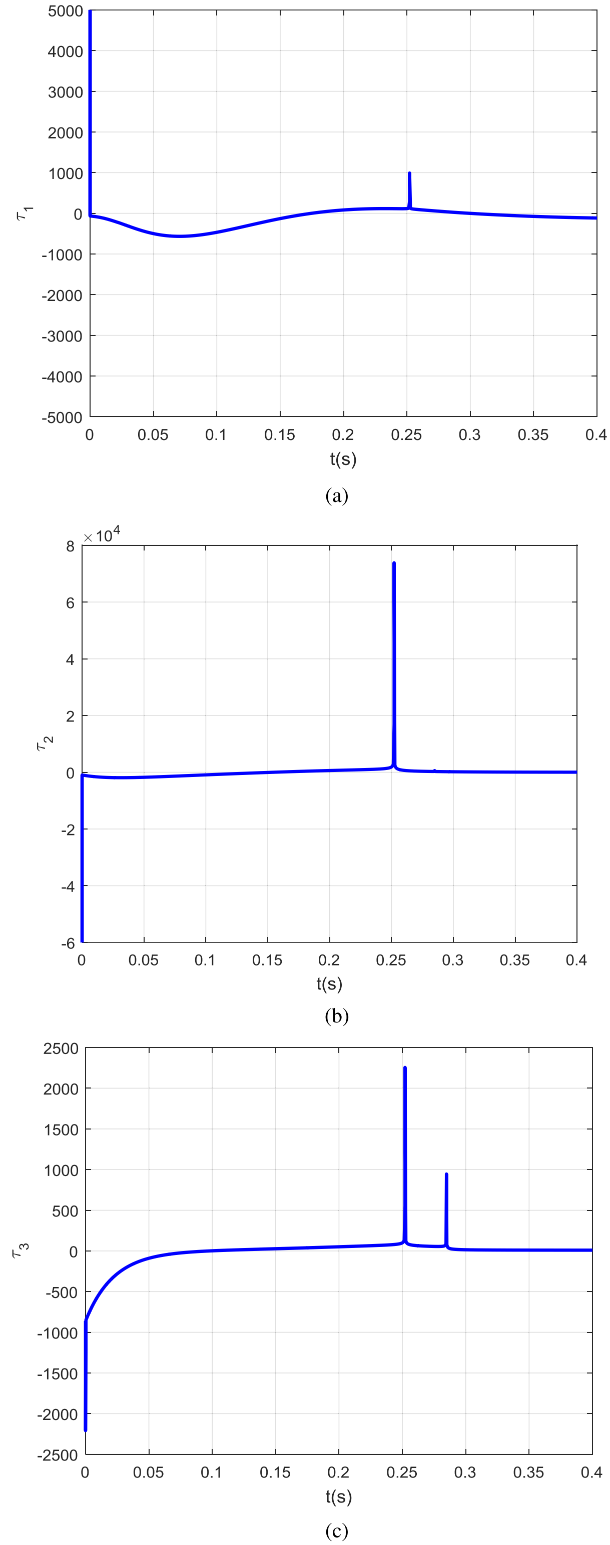

FIGURE 4. The singular finite-time backstepping control signal.

The nonsingular finite-time backstepping controller's parameters are selected as: $l_1 = diag(200, 200, 200)$, $l_2 = diag(4000, 4000, 4000)$, $k_1 = diag(0.05, 0.05, 0.05)$, $k_2 = diag(120, 120, 120)$, $\rho_1 = 10$, $\rho_2 = 10$, $\gamma = 0.6$,

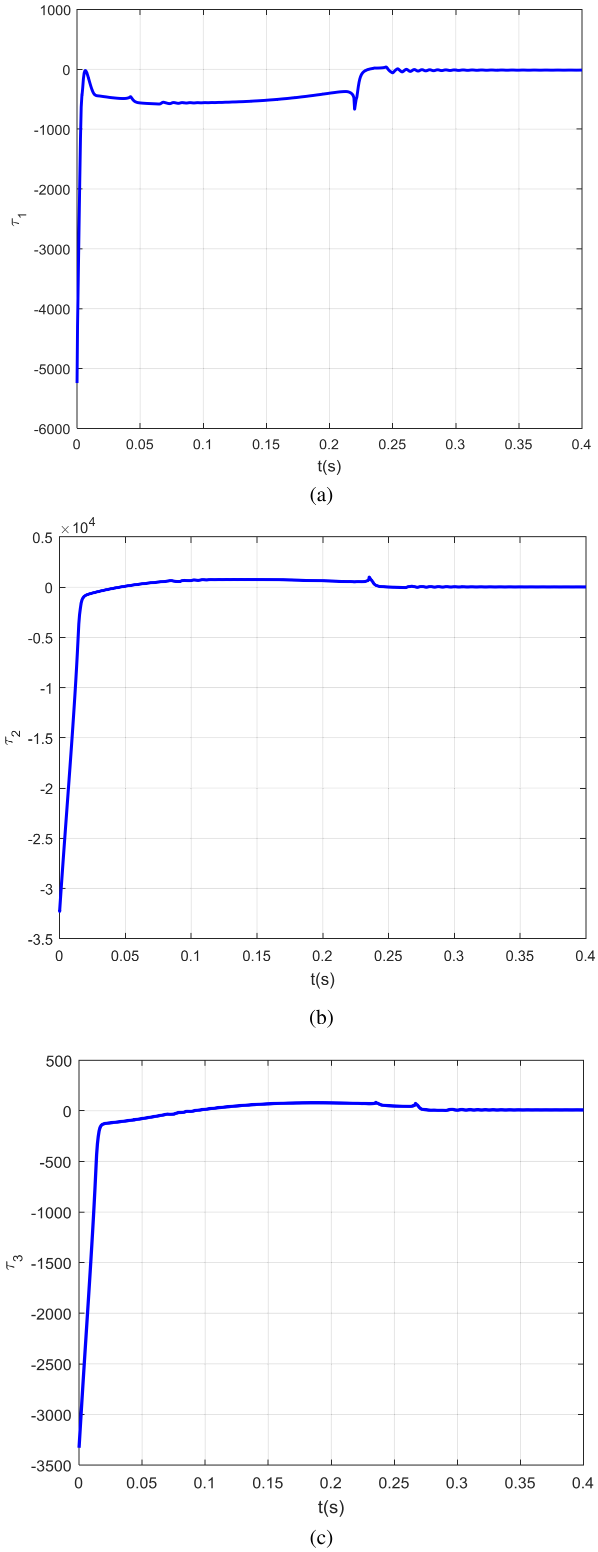

FIGURE 5. **The nonsingular finite-time backstepping control signal.**

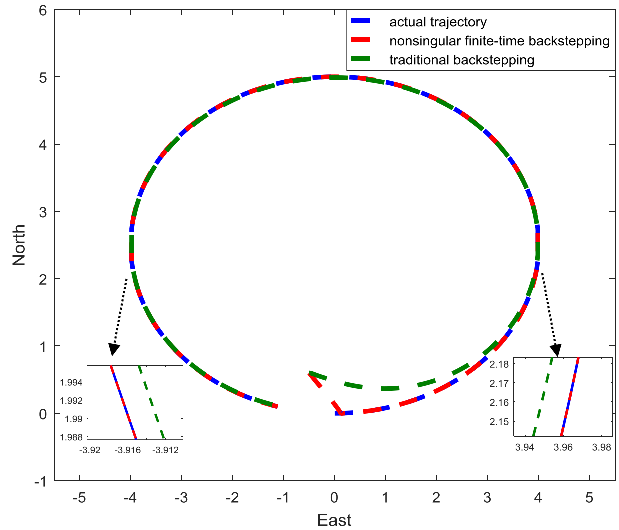

FIGURE 6. **The trajectory under the nonsingular finite-time backstepping and the traditional backstepping.**

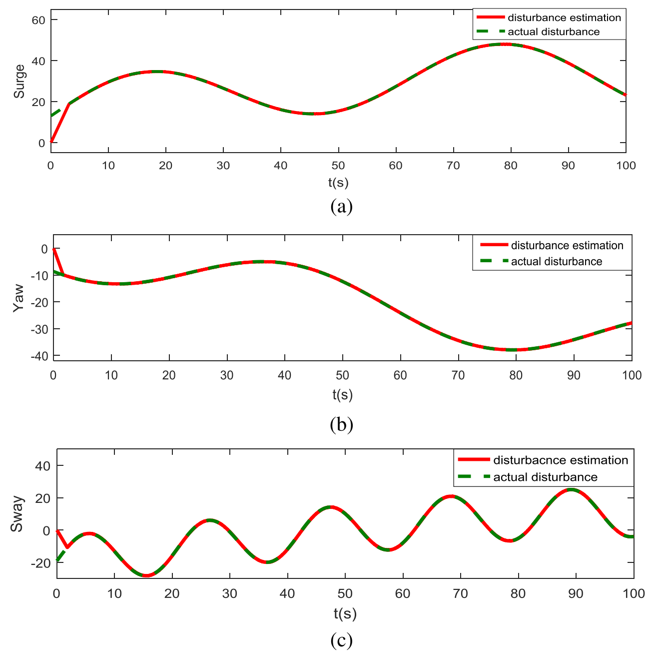

FIGURE 7. **Actual disturbances and their estimation by the proposed FTDO.**

the proposed FTDO's parameters are chosen as: $\kappa_1 = diag(20, 20, 20)$, $\kappa_2 = diag(6, 6, 6)$.

In order to show the proposed control law's superiority, we adopt the nonsingular finite-time backstepping control law to compare with singular finite-time backstepping control law and traditional backstepping control law as follow:

Traditional backstepping control:

$$\begin{cases} \alpha = R^T(-k_1 z_1 + \dot{\eta}_d) \\ \tau = (C+D)v + M\dot{\alpha} - R^T z_1 - k_2 z_2 - \hat{d} \end{cases} \tag{46}$$

Singular finite-time backstepping control:

$$\begin{cases} \alpha = R^T(-k_1 z_1 + \dot{\eta}_d - s_1|z_1|^\gamma sign(z_1)) \\ \tau = (C+D)v + M\dot{\alpha} - R^T z_1 - k_2 z_2 - d \\ \quad - s_2|z_2|^\gamma sign(z_2) \end{cases} \tag{47}$$

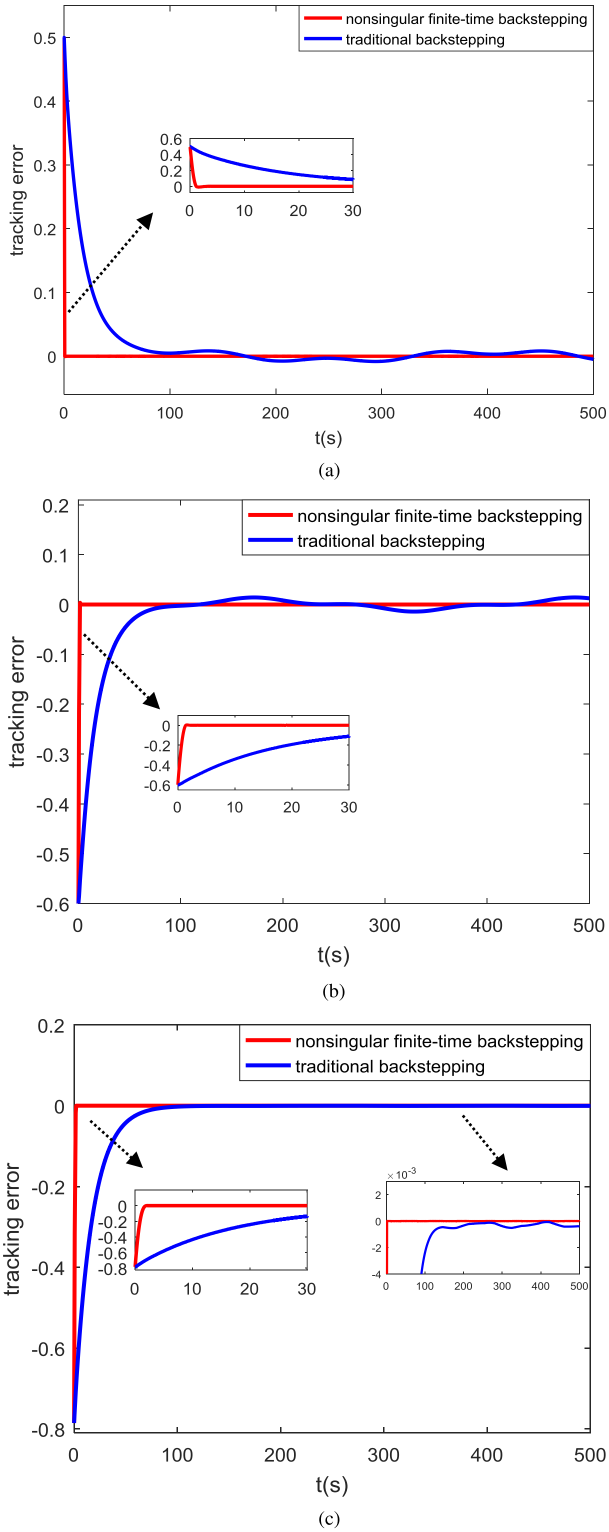

FIGURE 8. Position tracking error under the nonsingular finite-time backstepping and the traditional backstepping.

Nonsingular finite-time backstepping control:

$$\begin{cases} \alpha = R^T(-k_1 z_1 + \dot{\eta}_d - s_1|\omega_1|^\gamma sign(\omega_1)) \\ \tau = (C+D)v + M\dot{\beta} - R^T\omega_1 - k_2 z_2 - d \\ \quad - s_2|\omega_2|^\gamma sign(\omega_2) \end{cases} \tag{48}$$

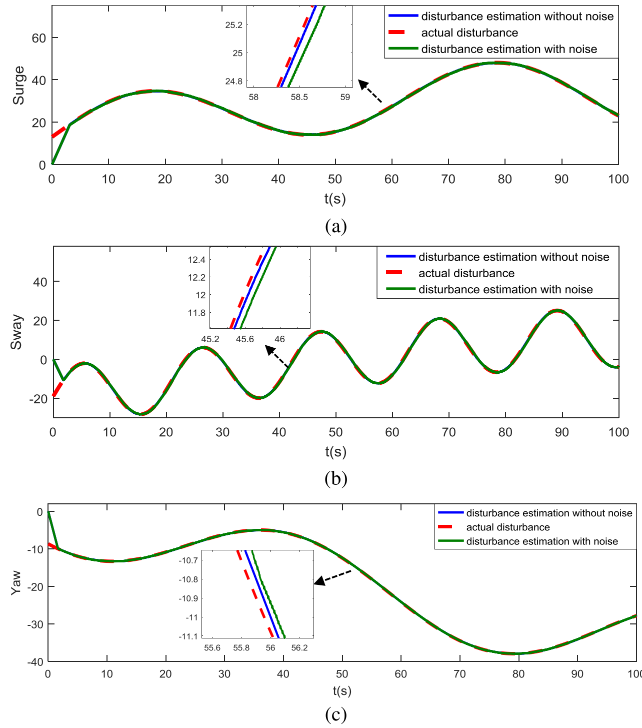

FIGURE 9. The estimation results of the FTDO used with and without measurement noise.

where ω_1 and ω_2 are defined in Section 4B, $\dot{\beta}$ is the finite-time command filter's output.

For fair comparisons, the parameters of the virtual control α and the control law τ above are chosen equally. The reference trajectory is equivalently planned according to [6] and [14]:

$$\begin{cases} x_d = 4sin(0.02t) \\ y_d = 2.5(1 - \cos(0.02t)) \\ \psi = 0.02t \end{cases} \tag{49}$$

The unknown disturbance is considered as:

$$\begin{cases} d_1 = x_d = 13 + 20sin(0.02t) + 15sin(0.1t) \\ d_2 = y_d = -9 + 20sin(0.02t - pi/6) + 15sin(0.3t) \\ d_3 = \psi = -10sin(0.09t + pi/3) - 40sin(0.01t) \end{cases} \tag{50}$$

From the Fig. 3, Fig. 6 and Fig. 8, we can obtain that nonsingular finite-time backstepping approach is faster and more accurate to track actual trajectory than the singular finite-time backstepping approach and the traditional backstepping approach. From the Fig. 4, we can see that it will occur the singular problem in the beginning of simulation and in time 0.25s. However, the proposed controller is nonsingular as shown in the Fig. 5. In the Fig. 7, it is observed that the proposed FTDO is able to estimate the unknown disturbances. It is obviously shown that the proposed controller can force the trajectory tracking error to reach zero in finite time.

From the figures above, we can obtain that the proposed method has better tracking performance than the traditional backstepping approach. Simultaneously, it also can avoid the singular phenomenon compared with the singular finite-time backstepping approach.

Comment 1: The unknown disturbance in equation (50) is considered. In Fig. 9, the estimation accuracy with and without noise is compared by our proposed FTDO, it can be seen that the real disturbance is better estimated by the FTDO in working without the noise, but the one with noise also satisfies the practical usage in a small bias. Therefore, the estimation with noise can be completed, and our proposed FTDO is robust for overcoming the unknown disturbance.

VII. CONCLUSION

In this paper, for precisely estimating the unknown external disturbances, the FTDO is designed firstly. Secondly, a novel singular finite-time backstepping controller is designed for marine vessel trajectory tracking considering unknown external disturbances. In order to avoid the singular phenomenon, we introduce a finite-time command filter, which can filter input signal quickly and estimate virtual control's derivative, instead of calculating it directly. Then, the simulation results made by our proposed control scheme have better control performance than the singular finite-time backstepping approach and the traditional backstepping approach. For the future work, due to complex marine environment, fault-tolerant control and input saturation for the trajectory tracking of marine vessels will be considered to improve control system performance.

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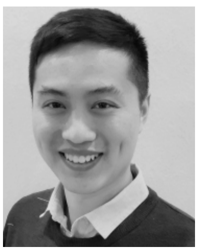

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