Trajectory Tracking Control of Surface Vehicles: A Prescribed Performance Fixed-Time Control Approach

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This work was supported by the National Natural Science Foundation of China under Grant 61573136.

ABSTRACT This article focuses on the fixed-time trajectory tracking problem for surface vehicles (SVs) with prescribed performance. First, to realize prescribed performance, the error transformation and fixed-time prescribed performance function are proposed. In this way, the constrained tracking error problem can be solved by the stabilization of the transformed system. Second, by introducing a reduced-order disturbance observer, a fixed-time sliding mode controller is developed to realize trajectory tracking control while satisfying both predefined performance and perturbation rejection. It notices that the associated settling time can be preselected by parameters and independent of system initial conditions. Finally, some simulation examples are provided to illustrate the effectiveness of our theoretical results.

INDEX TERMS Surface vehicles, prescribed performance, fixed-time observer, sliding mode control.

I. INTRODUCTION

Motion control of surface vehicles is particularly interesting and has many applications in practice, such as the self-guiding of unmanned driving vehicles, platform supplying, mine sweeping, and so on. Among the applications, guaranteeing that SVs can autonomously track a predefined trajectory in the complex ocean environment is a crucial issue. However, the high dynamic nonlinearities, unknown disturbances, and the behavior limitations of the vehicle make trajectory tracking control challenging [1]–[4].

To improve the tracking control accuracy of SVs, some alternative methods can be applied, such as sliding mode control [5], backstepping control method [6], $H_\infty$ control [7], model predictive control [8], particle filter [9], neural networks [10] and so on. It has been reported in [11] that the stability of the SV control system includes asymptotic, finite-time and fixed-time performances. Different from [5], [7] and [12] where the asymptotic stability is obtained, more effective strategies are expected to be designed to shorten the convergence time and enhance the system performance. In [13] and [14], the finite-time fault-tolerant control of an autonomous surface vehicle is proposed, and a finite-time control approach for accurate trajectory tracking control method for improvement is proposed in [15]. To pursue better convergence performance, the terminal sliding mode technique is deployed in [16]. Recently, sliding mode observer with finite-time reachability is presented in [17]–[19]. However, the convergence time is dependent on the initial values. Recently, a fixed-time algorithm is developed to formulate the maximum convergence time. In [20], a nonsingular sliding mode fixed-time tracking algorithm is proposed and extended for the tracking control of SVs with uncertainties and unknown actuator faults in [21]. Fruitful researches of fixed-time sliding model control (FTSMC) have been reported in the tracking control of SVs. Although fast convergence without singularity has been achieved by the FTSMC approach, it still falls into the issue that the transient performance of the tracking system cannot be guaranteed.

Recently, some control schemes with the prescribed performance have been studied for different systems. With the prescribed performance function (PPF) first developed by [22], the desired tracking error will converge to an arbitrarily small residual set, with the convergence rate no less than a prespecified value. In [23], Zhang proposes event-triggered control with prescribed performance and finite-time convergence for the nonlinear system. The work in [24] introduces the prescribed performance control in a dynamic surface

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control approach, Shahvali designs a neural adaptive control method for Euler-Lagrange systems. In [25], a novel adaptive path-following control is presented for mobile robots by the PPC method. In [26], the tracking control is proposed for underwater vehicles subject to external disturbances and thrust fault. In [27], the asymptotic trajectory tracking control with guaranteed transient behavior for surface vehicles subject to uncertainties is introduced. However, the majority of PPC controllers can only meet the asymptotic convergence of tracking errors under prescribed performance constraints. In [28], Hua proposes a PPC method to achieve formation control of multiple quadrotors. However, the published method cannot guarantee the whole system to be finite-time stable. In [29], the barrier Lyapunov function is utilized to achieve the finite-time consensus control with prescribed performance, but the convergence time relies on the initial values of system parameters, which makes the practical applications more complex. Hence, proposing a low-complexity fixed-time control method while achieving the prescribed performance is of great significance.

In addition, to enhance the robustness of the closed-loop system, in [12] a nonlinear extended state observer is constructed to recover states and estimate disturbances, which can effectively improve the anti-disturbance performance. However, the estimation errors converge to zero asymptotically. In order to improve the disturbance estimation performance, in [30] a finite-time observer-based path maneuvering of underactuated unmanned surface vehicles with collision avoidance is proposed. In [21], a fixed-time extended state observer is stressed to improve the trajectory tracking performance, which eliminates the relation between error convergence time and the initial values. In [31], a fixed-time disturbance observer is presented for tracking control by reducing the estimation dimension, which is superior to [21] in terms of engineering complexity. Hence, to alleviate the burden and enhance the robustness of SVs, it is necessary and practical to design a fixed-time reduced-order observer to estimate the disturbances.

Motivated by the above observations, in order to simultaneously improve the transient response and perturbation rejection performances of the trajectory tracking control, a disturbance observer-based fixed-time trajectory tracking strategy is presented, while meeting the predefined transient performance designed by the proposed fixed-time PPF. The main contributions can be summarized as follows:

(1) A novel fixed-time PPF is proposed, whose convergence time can be set arbitrarily according to requirements. Compared with the existing exponential or finite-time PPFs, the settling time is independent of system initial conditions.

(2) An improved fixed-time sliding mode control law based on disturbance observer is developed. The tracking errors can converge to an arbitrarily small residual set, with the convergence rate no less than a prespecified value. In comparison with [21], the proposed controller obtains a better transient performance.

The paper is organized as follows. Section II is SV models and preliminaries. Section III gives the novel PPF and fixed-time sliding mode tracking control scheme with prescribed transient performance. Section IV gives numerical simulations and discussions. Conclusions are contained in Section V.

II. PRELIMINARIES

A. SYSTEM MODELING

As shown in Figure 1, the SV model is commonly defined in the earth-fixed frame $O_xY_z$ and the body-fixed frame $oXY$. An individual SV can be described as follows:

$$\dot{\eta} = R(\psi) v,$$

$$M \dot{v} = -C(v) v - D(v) v + \tau_p + \tau.$$

![Figure 1. Earth-fixed and body-fixed coordinate systems.](image)

where $\eta = [x, y, \psi]^T$ represents the actual positions and heading angle in the earth-fixed frame and $v = [u, v, r]^T$ represents the vector consisting of the surge velocity $u$, the sway velocity $v$, and the yaw angular velocity $r$. $\tau$ denotes the control input of the SV with $\tau = [\tau_x, \tau_y, \tau_z]^T$. $\tau_p = [\tau_{p1}, \tau_{p2}, \tau_{p3}]^T$ represents the unknown external disturbance due to winds, waves, and ocean currents in the body-fixed frame. The inertia matrix $M$, the matrices $C(v)$ and $D(v)$ can be given below:

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix},$$

$$C(v) = \begin{bmatrix} 0 & 0 & c_{13}(v) \\ 0 & 0 & c_{23}(v) \\ -c_{13}(v) & -c_{23}(v) & 0 \end{bmatrix},$$

$$D(v) = \begin{bmatrix} d_{11}(v) & 0 & 0 \\ 0 & d_{22}(v) & d_{23}(v) \\ 0 & d_{32}(v) & d_{33}(v) \end{bmatrix},$$

where $m_{11} = m - X_u$, $m_{22} = m - Y_v$, $m_{23} = m_x - Y_t$, $m_{32} = m_x - N_v$, $m_{33} = I_z - N_t$, $c_{13}(v) = -m_{11}v - m_{23}r$, $c_{23}(v) = -m_{11}u$, $d_{11}(v) = -X_u - X_{u|u}|u| - X_{uu}u^2$, $d_{22}(v) = -Y_v - Y_{v|v}|v|$, $d_{23}(v) = -Y_t - Y_{t|v}|v|$, $d_{32}(v) = -N_v - N_{v|v}|v| - N_{v|v}|v|$, $d_{33}(v) = -N_t - N_{t|v}|v|$, $I_z$ denotes the inertial moment about yaw rotation.
and \( Y_f = N_f \). Additionally, \( X_s, Y_s \) and \( Z_s \) are hydrodynamic derivatives. The rotation matrix \( R(\psi) \) is given as:

\[
R(\psi) = \begin{bmatrix}
\cos(\psi) & -\sin(\psi) & 0 \\
\sin(\psi) & \cos(\psi) & 0 \\
0 & 0 & 1
\end{bmatrix},
\]

(3)

where \( R^T(\psi)R(\psi) = I \), and \( \dot{R}(\psi) = R(\psi)S(r) \)

with \( S(r) = \begin{bmatrix} 0 & -r & 0 \\
r & 0 & 0 \\
0 & 0 & 0 \end{bmatrix} \).

As pointed out in [32] and [33] that the damping effects are the results of several hydrodynamic phenomena, including potential damping, skin friction, wave drift damping, and the damping due to vortex shedding, which make accurate modeling for hydrodynamic damping effects difficult. Hence, the following assumption is given in this article.

**Assumption 1 ([34]):** The unknown time-varying external disturbance \( \tau_p \) is first differentiable, i.e., there exists a finite constant \( \tau_{p0} \) satisfying \( \| \tau_p \| < \tau_{p0} \).

The reference tracking trajectory is described as follows:

\[
\dot{\eta}_d = R(\psi)_d \nu_d, \quad M \dot{\nu}_d = -C(\nu_d) \nu_d - D(\nu_d) \nu_d + \nu_d, \quad \tau_d,
\]

(4a)

where \( \eta_d = [x_d, y_d, \psi_d]^T \) and \( \nu_d = [u_d, v_d, \nu_d]^T \) represent the desired general position and velocity vectors of the leader SV, respectively. \( \tau_d \) denotes the control input of the leader SV.

Before moving on, we present some definitions of fixed-time stability.

**Definition 1 ([35], [36]):** Consider the system defined by

\[
\dot{z}(t) = f(t, z(t)), \quad t \in R_+, z(0) = z_0,
\]

(5)

where \( z \in R^m \) is the state vector, \( f : R_+ \times R^m \rightarrow R^m \) is a nonlinear vector field locally bounded in time. The origin of system (5) is said to be globally uniformly finite-time stable if it is globally asymptotically stable and there exists a locally bounded function \( T : R^m \rightarrow R_+ \cup \{0\} \), such that \( z(t, z_0) = 0 \) for all \( t \geq T(z_0) \), and \( T(z_0) \) is called the settling-time function.

**Definition 2 ([35], [36]):** If the system (5) is globally finite-time stable and there exists a positive constant \( T_{max} \) such that \( T < T_{max} \), that is to say, the convergence time \( T \) is bounded. Therefore, it is said to be fixed-time stable.

Defining \( \sigma = [\sigma_1, \sigma_2, \ldots, \sigma_d]^T \in R^n \) and \( \text{sign}^a(\sigma) = [\text{sign}^a(\sigma_1), \text{sign}^a(\sigma_2), \ldots, \text{sign}^a(\sigma_d)]^T \), where \( \text{sign}^a(\sigma_i) = [\text{sign}(\sigma_i)(i = 1, \ldots, n) \text{ and } a \in (0, 1)] \), \( \text{sign}(\sigma) \) is the function defined below,

\[
\text{sign}(\sigma) = \begin{cases} 
-1, & \text{if } \sigma < 0, \\
[-1, 1], & \text{if } \sigma = 0, \\
1, & \text{if } \sigma > 0.
\end{cases}
\]

(6)

In addition, \( |\cdot| \) represents the absolute value of a scalar. Then we have the following lemma.

**Lemma 1 ([21]):** If system (5) satisfies the equation below,

\[
\dot{z} = -l_1\text{sign}^a(z) - l_2\text{sign}^a(z), \quad x(0) = x_0,
\]

(7)

where the parameters satisfy \( 0 < n < 1, m > 1, l_1 > 1, l_2 > 0 \). Then the above system is fixed-time stable and the settling time is expressed as

\[
T \leq \frac{1}{l_1(m-1)} + \frac{1}{l_2(1-n)}.
\]

(8)

**B. OBJECTIVE**

The objective of this article is to propose a fixed-time control scheme for model (1) with unknown lumped disturbances, so that the reference trajectory (4) can be tracked in fixed time while satisfying the prescribed performance. Define the tracking error as \( e_1 = \eta - \eta_d \), then the objective can be described as the constrained problem below,

\[
-\delta_k \rho_k < e_{1k} < \rho_k,
\]

(9)

where \( 0 < \delta_k \leq 1, k = 1, 2, 3. \rho_k \) is a prescribed performance function (PPF) designed in next section. By equation (9), the tracking error \( e_1 \) can converge to an arbitrarily small residual set with respect to the designed PPF \( \rho_k \).

**Assumption 2 ([31]):** The initial tracking error satisfies \( e_{1k}(0) \geq 0 \). The condition \( e_{1k}(0) < 0 \) is omitted for simplicity.

**Remark 1:** Tracking problem of SVs subject to uncertainties, external disturbances has been considered in literatures [3], [21], [37], making the proposed controller robust to a more extensive and challenging environment. However, few works analyze the prescribed performance of the transient response in the control process. In complex external environments, a high demand over system transient performance should be met.

**Remark 2:** The fixed-time tracking control theory is proposed in this article. Compared with [14], [19], [37], [44], the settling time is independent of initial conditions. In addition, as for Assumption 1, if the condition of \( e_{1k}(0) < 0 \) is satisfied, then the tracking error \( e_{1k} \) will converge to the set of \(-\rho_k < e_{1k} < \delta_k \rho_k \). Due to the fact that the controller design method is similar to the case of \( e_{1k}(0) \geq 0 \), it is omitted for space constraints. The paper [31] can be referred to for more details.

**III. FIXED-TIME PRESCRIBED PERFORMANCE TRACKING CONTROL**

**A. PRESCRIBED PERFORMANCE FUNCTION DESIGN**

In this article, a second-order fixed-time PPF \( \rho_k \) inspired by [38] is designed below:

\[
\dot{\rho}_k = -\mu_1(\rho_k - \rho_{k\infty})^{\alpha_{11}} \text{sign} \left( \rho_k - \rho_{k\infty} \right)
+ |\rho_k - \rho_{k\infty}|^{\beta_{21}} \text{sign} \left( \rho_k - \rho_{k\infty} \right)
- \mu_2(\dot{\rho}_k)^{\alpha_{21}} \text{sign} \left( \dot{\rho}_k \right)
+ |\dot{\rho}_k|^{|\beta_{21}} \text{sign} \left( \dot{\rho}_k \right)
\]

\[
\rho_k(0) = \rho_{0,k}, \quad \dot{\rho}_k(0) = 0,
\]

(10)

where the parameters \( \alpha_{11}, \beta_{11} (i = 1, 2) \) can be chosen as \( \alpha_{11} = \kappa/(2-\kappa), \alpha_{21} = \kappa, \beta_{11} = (2-\kappa)\kappa \) and \( \beta_{21} = 2 - \kappa \)
with $\bar{\vartheta} \in (0, 1)$ and $\kappa \in (\bar{\vartheta}, 1)$. $\mu_{i} > 0$ ($i = 1, 2$) satisfies that both the polynomial $s^{2} + \mu_{2}s + \mu_{1}$ and $s^{2} + 2\mu_{2}s + 3\mu_{1}$ are Hurwitz in terms of the Laplace operator $s$, which means that $\mu_{1} > 0$ and $\mu_{2} > 0$. Based on the novel PPF $\rho_{k}$, one important result is stated as follows.

**Lemma 2:** For prescribed performance function in (10), if $\rho_{0,k} > \rho_{k,\infty}$, then it has

$$\rho_{k}(t) = \rho_{k,\infty}, \quad \forall t \geq T_{1},$$

where $T_{1}$ is a positive constant depending on parameters $\mu_{i}$, $\alpha_{i1}$ and $\beta_{i1}$ ($i = 1, 2$).

The proof could be derived by following the same line as the proof of Lemma 2 given in the recent work [38].

**Remark 3:** Different PPFs have been designed in previous literatures. The traditional PPF is given below [39], [40]:

$$\rho = (\rho_{0} - \rho_{\infty}) e^{-at} + \rho_{\infty}, \quad (12)$$

where $a$ is the prescribed positive constant. In [31], the modified Hyperbolic cosecant PPF is given:

$$\rho = \text{csch}(at + \rho_{0}) + \rho_{\infty}, \quad (13)$$

with $\text{csch}(x) = 1/(e^{x} - e^{-x})$. The above functions own asymptotic decaying rate. In [41], the finite time PPF is proposed as follows:

$$\dot{\rho}_{k} = -\mu |\rho_{k}(t) - \rho_{k,\infty}|^{\beta_{2}} \text{sign}(\rho_{k}(t) - \rho_{k,\infty}), \quad (14)$$

and the the dwell time is

$$T_{2} = \frac{(\rho_{0}(k) - \rho_{k,\infty})^{\beta_{2}+1}}{\mu(1 - \beta_{2})}, \quad (15)$$

with $\beta_{2} \in (0, 1)$, which depends on the initial value of $\rho_{k}(t)$. Due to the fact that $\rho_{0}(k) > |e_{1k}(0)|$ should be satisfied, when the initial tracking error $|e_{1k}(0)|$ is large, that is to say, the distance between the follower SV and the leader SV is large, then it results a larger $\rho_{k}(0)$. According to equation (15), the finite time convergence time is large, which may influence the transient response. In Figure 2, clearly, with the finite-time PPF of case 1 and case 2, a larger initial value results in a larger dwell time. In (10) the fixed-time PPF is proposed. For comparison, the first-order fixed-time PPF is utilized here. From Lemma 1, we know the state variables will converge into the stability regions within the fixed time without the influence of the initial value $\rho_{k}(0)$, which is shown as the fixed-time PPF of case 1 and case 2. Besides, the convergence time can be preselected by the users and the difficulty in achieving the convergence performance by choosing parameter $a$ in (12) and (13) is omitted, which is user-friendly in practice. Second, the convergence time $T_{1}$ can be preselected by the users, which is easily achievable and owns a better transient response than the traditional asymptotic rate in (12) and (13).

**Remark 4:** In [35], new results about the settling time of fixed-time stability are proposed, the Gamma function is introduced. In [35], the result is less conservative and more accurate by $T_{1, max} = \frac{1}{\mu_{i}(\alpha_{i1} + \beta_{i1})^{2}}$. [35] can be referred to for deeper details.

Next, inspired by [23], through a transformation method, it is stipulated that the transient performance of the tracking error $e_{1k}$ in (9) is satisfied if the transformed error $\varepsilon_{k}$ below is always bounded. The transferred error $\varepsilon_{k}$ can be described as:

$$\varepsilon_{k} = \frac{1}{2} \ln \left( \frac{z_{k} + \delta_{k}}{1 - z_{k}} \right), \quad (16)$$

where $z_{k} = e_{1k}/\rho_{k}$, and $k = 1, 2, 3$ representing the symbols of position and angle tracking performances. The derivative of $z_{k}$ is $\dot{z}_{k} = \dot{e}_{1k}/\rho_{k}$, and the derivative of transferred error $\varepsilon_{k}$ can be expressed as:

$$\dot{\varepsilon}_{k} = \frac{\partial \varepsilon_{k}}{\partial z_{k}} \dot{z}_{k}$$

$$= \frac{\partial \varepsilon_{k}}{\partial z_{k}} \left( \frac{e_{1k}\rho_{k} - e_{1k} \dot{\rho}_{k}}{\rho_{k}^{2}} \right)$$

$$= \mathcal{T}_{k} \left( \dot{e}_{1k} - e_{1k} \frac{\dot{\rho}_{k}}{\rho_{k}} \right), \quad (17)$$

with $\mathcal{T}_{k} = \frac{\partial \varepsilon_{k}}{\partial z_{k}}$. Then the derivative of $\mathcal{T}_{k}$ is given as:

$$\dot{\mathcal{T}}_{k} = \frac{d(\mathcal{T}_{k})}{dt},$$

where

$$d(\mathcal{T}_{k}) = \frac{\partial}{\partial z_{k}} \left( \frac{1}{\rho_{k}} \dot{\rho}_{k} \right) = \frac{\dot{z}_{k} (1 + \delta_{k})(2 - 4z_{k} - 2\delta_{k})}{4(z_{k} + \delta_{k})^{2}}.$$
Define \( \varepsilon = [\varepsilon_1, \varepsilon_2, \varepsilon_3]^T \), the above equation (20) can be subsequently described in the compact form below:

\[
\dot{\varepsilon}_k = \tilde{T}_k \left( e_{1k} - \frac{e_{1k} \hat{p}_k}{\rho_k} \right) + \tau_k \left( e_{1k} - \frac{e_{1k} \hat{p}_k + e_{1k} \hat{p}_k \rho_k - e_{1k} \hat{p}_k^2}{\rho_k^2} \right).
\]

(20)

**Remark 5:**

The fixed-time disturbance observer is proposed in [22]. Compared with [5], [17]–[19], the settling time is independent of initial conditions.

To avoid the singularity problem, the fixed-time singularity-free sliding mode manifold motivated by [20] is introduced below:

\[
S_k = \varepsilon_k + \left[ \frac{1}{\bar{\alpha_1} e_k^{\frac{m}{n} - \frac{p}{q}} + \bar{\beta}_1} \right]^{\frac{q}{p}} \bar{e}_k.
\]

(23)

where \( m, n, p, q \) are positive odd integers satisfying \( m > n \), \( p < q < 2p, m/n - p/q > 1 \), \( \bar{\alpha}_1 \) and \( \bar{\beta}_1 \) are positive values.

Next, a novel fixed-time nonlinear tracking control law based on nonsingular sliding mode manifold while satisfying prescribed performance (9) is given.

**Theorem 1:** Consider the SV system in (1) with the feedback control law designed below:

\[
\tau = -f(\psi) - \dot{\bar{\varepsilon}}_k + MR^{-1}(\dot{\varepsilon} + \dot{\bar{\varepsilon}}_d - R(\psi) S(r(\psi)))
\]

\[
-\bar{M}R^{-1}\bar{R}(\psi) e - \dot{\bar{\varepsilon}}_d - \text{diag}(e_1) \text{diag}(\dot{\rho})
\]

\[
\times \rho^{-1} + (MR^{-1}\bar{R}(\psi) e - \dot{\bar{\varepsilon}}_d - \text{diag}(e_1) \text{diag}(\dot{\rho}) \rho^{-1})
\]

\[
\times (K\varepsilon - \bar{M}R^{-1}\bar{R}(\psi) e - \dot{\bar{\varepsilon}}_d - \text{diag}(e_1) \text{diag}(\dot{\rho}) \rho^{-1})
\]

\[
\times \sigma(\bar{\varepsilon}_k^{\frac{-1}{q}})(\bar{\alpha}_1 e_k^{\frac{m}{n} - \frac{p}{q}} + \bar{\beta}_1 e_k^{\frac{q}{p}}),
\]

(24)

with

\[
\sigma(\tilde{x}) = \begin{cases} \sin(\pi \tilde{x} / 2 \theta), & \text{if } \tilde{x} \leq \theta, \\ 1, & \text{otherwise}, \end{cases}
\]

(25)

where \( \theta \) is a positive constant, \( m_2, n_2, p_2 \) and \( q_2 \) are positive odd integers satisfying \( m_2 > n_2 \) and \( p_2 < q_2 \), respectively. \( \tau_p \) is the estimation of disturbance \( \tau \). The matrix \( K = \text{diag}(\bar{\alpha}_1 e_k^{\frac{m}{n} - \frac{p}{q}} + \bar{\beta}_1) \) for simplification. Then for any bounded initial condition satisfying Assumption 1, the tracking error \( e_1 \) can be ensured to remain within the given prescribed performance bounds (9), and converge to the adjustable small neighborhoods around zero in fixed time. Additionally, the upper bound of the convergence time is

\[
T < T_{max} = T_2 + T_3 + T_4,
\]

(26)

where \( T_3 \) and \( T_4 \) are defined later.

**Proof:** A Lyapunov candidate function is conducted below:

\[
V = \frac{1}{2} S^T S.
\]

(27)

Taking the derivative of (27) and combining (23) yields:

\[
\dot{V} = S^T (\dot{\varepsilon} + \frac{q}{p} (K\varepsilon)^{\frac{-1}{q}} (K\dot{\varepsilon} + K\varepsilon))
\]

(28)

The derivative of \( K_k \) is given as

\[
K_k = \frac{K}{\bar{\alpha}_1 e_k^{\frac{m}{n} - \frac{p}{q}} + \bar{\beta}_1} e_k^{\frac{q}{p}}.
\]

Subsequently, the equation (28) can be rewritten as follows:

\[
\dot{V} = S^T (\dot{\varepsilon} + \frac{q}{p} (K\varepsilon)^{\frac{-1}{q}}
\]

\[
\times [-\bar{\alpha}_1 \text{diag}(K\varepsilon)^{\frac{q}{p}} (m/n - p/q) e_k^{\frac{m}{n} - \frac{p}{q} - 1} + K\varepsilon])
\]

\[
= S^T (\dot{\varepsilon} + \frac{q}{p} (K\varepsilon)^{\frac{-1}{q}}
\]

\[
\times [-\bar{\alpha}_1 \text{diag}(K\varepsilon)^{\frac{q}{p}} (m/n - p/q) e_k^{\frac{m}{n} - \frac{p}{q} - 1} + K\varepsilon]
\]

\[
\times [-\bar{\alpha}_1 \text{diag}(K\varepsilon)^{\frac{q}{p}} (m/n - p/q) e_k^{\frac{m}{n} - \frac{p}{q} - 1} + K\varepsilon]
\]

\[
+ K\varepsilon (R(\psi) e - \dot{\bar{\varepsilon}}_d - \text{diag}(e_1) \text{diag}(\dot{\rho}) \rho^{-1})
\]

\[
+ \bar{R}(R(\psi) M^{-1}(f(\psi) + \tau_p + \tau)
\]

\[
+ R(\psi) S(r(\psi) e - \dot{\bar{\varepsilon}}_d - \text{diag}(e_1) \text{diag}(\dot{\rho}) \rho^{-1}))]
\]
Combining the control law (24) and disturbance observer (22) after $t > T_2$ yields:

$$
\dot{V} = -S^T \left( \bar{\alpha}_2 \sigma \left( \frac{\hat{e}^\sigma - 1}{\sigma} \right) S \frac{\dot{\varphi}_2}{2} + \bar{\beta}_2 \sigma \left( \frac{\hat{e}^\sigma - 1}{\sigma} \right) S \frac{\dot{\varphi}_2}{2} \right)
$$

$$
= -\bar{\alpha}_2 \sigma \left( \frac{\hat{e}^\sigma - 1}{\sigma} \right) S \frac{\dot{\varphi}_2}{2} - \bar{\beta}_2 \sigma \left( \frac{\hat{e}^\sigma - 1}{\sigma} \right) S \frac{\dot{\varphi}_2}{2}
$$

$$
= -\bar{\alpha}_2 \sigma \left( \frac{\hat{e}^\sigma - 1}{\sigma} \right) 2 \frac{\dot{\varphi}_2}{2} V \frac{\dot{\varphi}_2}{2}
$$

$$
- \bar{\beta}_2 \sigma \left( \frac{\hat{e}^\sigma - 1}{\sigma} \right) 2 \frac{\dot{\varphi}_2}{2} V \frac{\dot{\varphi}_2}{2}
$$

$$
= -\mathcal{N}_1 V \frac{\dot{\varphi}_2}{2} + \mathcal{N}_2 V \frac{\dot{\varphi}_2}{2},
$$

(29)

with $\mathcal{N}_1 = \bar{\alpha}_2 \sigma \left( \frac{\hat{e}^\sigma - 1}{\sigma} \right) 2 \frac{\dot{\varphi}_2}{2}$ and $\mathcal{N}_2 = \bar{\beta}_2 \sigma \left( \frac{\hat{e}^\sigma - 1}{\sigma} \right) 2 \frac{\dot{\varphi}_2}{2}$.

Observing function (25), if the system state $\hat{e}^\sigma - 1 > \theta$ holds, it has $\dot{S} = -\left(2 \frac{\dot{\varphi}_2}{2} + \bar{\beta}_2 \sigma \right)$. With Lemma 1, we can conclude that the sliding mode manifold will converge to zero within a fixed time, and the convergence time is bounded by

$$
T_3 \leq \frac{2}{\mathcal{N}_1 \left( \frac{\dot{\varphi}_2}{2} - 1 \right)} + \frac{2}{\mathcal{N}_2 \left(1 - \frac{\dot{\varphi}_2}{2} \right)}.
$$

(30)

After $t > T_2 + T_3$, the sliding mode surface is reached and $S = 0$. Then we have $\dot{e}_k = -\left[ \frac{1}{\sigma_1 \sigma_2} \frac{\dot{e}_k}{\sigma_1 \sigma_2} \right]$ and $\dot{\hat{e}} = -\bar{\alpha}_1 \sigma \frac{\dot{e}_k}{\sigma_1 \sigma_2} - \bar{\beta}_1 \sigma \frac{\dot{e}_k}{\sigma_1 \sigma_2}$, with Lemma 1, $\dot{\hat{e}}$ will converge within the range of $\dot{e}_k$ $\leq \theta$ in fixed-time $T_4 \leq \frac{1}{\sigma_1 \left( \frac{\dot{\varphi}_2}{2} - 1 \right)} + \frac{1}{\sigma_1 \left( \frac{\dot{\varphi}_2}{2} - 1 \right)}$.

If $\dot{e}^\sigma - 1 \leq \theta$, that is to say, $|\dot{e}_k| \leq \theta V_2$, it gives

$$
\dot{V} = -\mathcal{N}_1 V \frac{\dot{\varphi}_2}{2} - \mathcal{N}_2 V \frac{\dot{\varphi}_2}{2},
$$

(31)

Due to the fact that $\sigma \left( \frac{\dot{e}^\sigma - 1}{\sigma} \right) > 0$, the sliding mode surface $S$ is still the region of attraction. Meanwhile, after $t \geq T_2$, subsequently, we have

$$
\dot{\hat{e}} = \mathcal{R} \left( R \left( \psi \right) M^{-1} \mathcal{R}_p \right) + K^{-1} [\mathcal{R}_t \left( \frac{m}{n} \right) - \frac{p}{q}] \times \text{diag}(\mathcal{K} \dot{\hat{e}}^2) \dot{\hat{e}} \frac{\dot{\varphi}_2}{2} - \frac{P}{q} K^{-1} \frac{\dot{\varphi}_2}{2} \frac{\dot{\varphi}_2}{2}
$$

$$
= \left( K^{-1} [\mathcal{R}_t \left( \frac{m}{n} \right) - \frac{p}{q}] \text{diag}(\mathcal{K} \dot{\hat{e}}^2) \dot{\hat{e}} \frac{\dot{\varphi}_2}{2} - \frac{P}{q} K^{-1} \frac{\dot{\varphi}_2}{2} \frac{\dot{\varphi}_2}{2}
$$

$$
= \left( K^{-1} [\mathcal{R}_t \left( \frac{m}{n} \right) - \frac{p}{q}] \text{diag}(\mathcal{K} \dot{\hat{e}}^2) \dot{\hat{e}} \frac{\dot{\varphi}_2}{2} - \frac{P}{q} K^{-1} \frac{\dot{\varphi}_2}{2} \frac{\dot{\varphi}_2}{2}
$$

Clearly, it has $\lim_{\dot{e}_k \to 0} \dot{\hat{e}} = 0$, and the origin is the unique equilibrium point. The system states $\hat{e}$ and $\dot{\hat{e}}$ will be guaranteed on the surface $S = 0$, or converge to a small region that $|\dot{e}_k| \leq \theta V_2$. With the transformation method (16), the tracking error $e_1$ can be ensured to remain within the given prescribed performance bounds (9). The proof is completed.

Remark 6: The traditional trajectory tracking error is converted into the specified performance state (16) by utilizing the fixed time PPF (10) and error transformation equation (16). The fixed-time sliding mode controller design is equivalent to that of a second-order system like suspension systems, and it can be extended to the high-order nonlinear system such as [45] with the backstepping method. Besides, the fixed-time disturbance observer design in (22) can improve the robustness of the proposed controller.

To sum up with the main results, we give the following algorithm in Table 1 and the control scheme diagram in Figure 3 for implementation of the presented tracking method.

**TABLE 1. Trajectory Tracking Control Algorithm of SVs.**

1. Give the desired tracking trajectory (4a-4b).
2. Design parameters $\alpha_1, \beta_1, \beta_2, \infty$ in fixed-time PPF (10).
3. Choose parameters $\delta_1$ in error transformation (16).
4. Design the fixed-time reduced-order disturbance observer in (22).
5. Design the control input $\tau$ as (24), and choose control parameters $m, \sigma, q, n, \alpha_2, \beta_2$ and $\varphi_2$.

**FIGURE 3. The Fixed Time Scheme Diagram.**
TABLE 2. The Parameters for CyberShip II.

| Parameter | Value |
|-----------|-------|
| m         | 23.80000 |
| I_p       | 1.7600   |
| x_p       | 0.0460   |
| X_u       | 0.7225   |
| X_0       | -1.3274  |
| X_1       | -5.8664  |
| Y_p       | -36.2823 |
| Y_u       | 0.1079   |
| Y_0       | 0.1052   |
| N_0       | 5.0457   |
| N_1       | -1.0     |
| N_2       | -0.8450  |
| N_3       | 0.0      |
| N_4       | 0.0      |

The estimations for disturbances $\tau_p$ are shown in Figures 4-6, which implies the fixed-time reduced-order observer (10) can estimate the disturbances in a fixed time. In Figure 7, the performance comparison of disturbance estimation is given between our paper and [5] described below:

\[
\begin{align*}
\dot{z}_0 &= \epsilon_0 - (C + D)v + \tau \\
\dot{z}_1 &= \epsilon_1 \\
\dot{z}_2 &= \epsilon_2 
\end{align*}
\]  

(35)

The parameters are chosen as $\lambda_0 = 3$, $\lambda_1 = 2$, $\lambda_2 = 2$, and $L = 1$. Two different initial values of the observer are given as $[0 0 0]^T$ and $[0.6 0 0]^T$, which are respectively shown as estimation in [5]a and [5]b in Figure 7. Compared with the fixed-time disturbance observer (22), the settling time in [5] is influenced by the initial conditions. Besides, the settling time in (22) can be predesigned by choosing parameters $\alpha_0$ and $\beta_0$.

To demonstrate the effectiveness of the tracking control scheme under the proposed controller in (24) with fixed-time reduced-order disturbance observer method, the simulation comparisons are presented in different cases between the proposed prescribed performance method and the existing tracking schemes of SVs in [21] and [15], whose control laws are given below:

\[
\begin{align*}
\tau_n &= -MR^{-1} K \gamma_2 \Theta \text{diag}(\rho^T(\omega e)) \text{diag}(\rho(\omega e)) \\
&\times [\text{sig}(S) + \text{sig}(S) + S] + \dot{\chi} + Z - \dot{\omega}_d 
\end{align*}
\]  

(36)

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(2) Wang’s finite-time trajectory tracking controller in [15], which is called FNT for simplify. The sliding mode surface is designed as

\[ S = \eta_e + k_1 \text{sig}^{\mu}(\eta_e) + k_1 \text{sig}^{\mu/2}(\eta_e). \]  

The controller is given below:

\[
\tau = -MR^{-1}\left(\frac{q}{pk_2}(R\nu - R_d\nu_d)^{2-p/q}\right)
\times (k_1 \mu \text{diag}(\| \eta - \eta_d \|^\mu - I)
+ S_d R_d \nu_d + R_d M^{-1} \nu_d + k_4 \text{sign}(\sigma)
- R_d M^{-1} (C(\nu_d) + D(\nu_d)) \nu_d + k_3 \sigma + z_1)
- MS \nu + (C(\nu) + D(\nu) \nu + g(\eta, \nu)).
\]  

(3) Our proposed controller in (24), which is called FTSM-PPF for simplify.

The control parameters of the above controllers are given in Table 3.

**TABLE 3. Controller Parameters.**

| Controller Parameters | FTSM-PPF | FTSM | FNT |
|-----------------------|----------|------|-----|
| Control parameters    |          |      |     |
|                        |          |      |     |

The initial position and yaw angle of the SV are given as \( \eta(0) = [9, 6, \pi/4]^T \), the initial velocity of the SV is given as \( \nu(0) = [0.2, 0.1, 0.3]^T \) in case 1, and \( \eta(0) = [6, 5, \pi/4]^T \), \( \nu(0) = [0.2, 0.1, 0.3]^T \) in case 2. The variable \( \rho_{\infty} \) in PPF (10) of both cases are chosen as 0.4 and \( \mu = 0.3 \). With equation (26), the settling time of transient response by the fixed-time prescribed performance controller (24) is obtained as 

\[ T_{\text{max}} = T_2 + T_3 + T_4 = 5.756s, \]

which means that for any bounded initial condition, the tracking error can be ensured to remain within the given prescribed performance bounds (9), and converge to the adjustable small neighborhoods around zero in fixed time \( T_{\text{max}} \).

The transient performance comparisons of tracking errors are shown in Figures 8-11. Figures 8-9 depict the three tracking error state variables \( x_e \) of FTSM-PPF, FTSM and FNT.
in Case 1 and Case 2, respectively. Figures 10-11 depict the three tracking error state variables $y_e$ of FTSM-PPF, FTSM and FNT in Case 1 and Case 2, respectively.

It is obvious that the proposed fixed-time PPC controller achieves the prescribed performance in (9), and the tracking errors can converge towards the prescribed performance function (10). Since the convergence time of finite-time controllers depends on the initial values of systems, in Figure 8 large initial values in FNT cannot guarantee the transient performance compared with small ones in Figure 8. Similarly, Figures 10-11 show the three tracking error state variables $y_e$ in Case 1 and Case 2, the tracking error $y_e$ achieves the prescribed performance in (9). The error $y_e$ of FNT in Figure 10 cannot guarantee the transient performance compared with small ones in Figure 11. The tracking errors for FTSM-PPF are slightly superior to FTSM and FNT. The motion of the SV in the horizontal plane is shown in Figure 12. In Figures 13-14, the variable $\rho_\infty$ in PPF (10) of case 2 is chosen as 0.2, which proofs the tracking errors can converge to the adjustable small neighborhoods around zero in the fixed time.

V. CONCLUSION

In this article, a novel fixed-time prescribed performance tracking scheme is proposed for SVs with unknown disturbances. The fixed-time prescribed performance function and the fixed-time reduced-order disturbance observer are proposed. Combining the singularity-free sliding mode technique, fixed-time controllers are designed to guarantee that the tracking errors are within the predefined bounds. Thus, both transient and steady performances can be achieved using the proposed tracking control law. Simulation results illustrate the effectiveness of the proposed methods. Future work includes the relation of the proposed solution with other kinds of methods such as obstacle avoidance and multi-agent systems. Moreover, since the sensor fault may exist, and the event-triggered mechanism can reduce the burden of communication that may be interesting and meaningful for the complex ocean environment; both of these will be chosen as our future directions.

ACKNOWLEDGMENT

The authors would like to thank the associate editor and reviewers for all their very valuable suggestions and comments which have helped to improve the presentation and quality of the paper.

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