Event-Triggered Adaptive Practical Fixed-Time Trajectory Tracking Control for Unmanned Surface Vehicle

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***Abstract*—This brief investigates the fixed-time trajectory tracking control problem for unmanned surface vehicle with unknown dynamics based on command filtered backstepping technique and fixed-time stability theory. Distinct from the existing results where the control execution is periodic and the computational burden is overlarge, a novel event-triggered adaptive practical fixed-time fuzzy controller is designed to guarantee the fixed-time stability of the closed-loop system (CLS), where the controller is aperiodically updated only at the event-sampled instants. Theoretical analysis proves that the tracking errors can diminish to an arbitrarily small neighborhood of the origin within a fixed time interval and the prescribed convergence time is free of the initial states of the surface vehicle under the proposed control method. Finally, the simulation results are provided to demonstrate the validity of the developed control approach.**

***Index Terms*—Command-filtered backstepping technique, event-triggered control, fixed-time stability, trajectory tracking control, unmanned surface vehicle.**

I. Introduction

Over the past decades, various efforts have been devoted to the study of the various unmanned vehicles such as unmanned surface vehicle (USV) and unmanned aerial vehicles (UAV) owning to their huge application potential in civil aviation and military affairs [1]. Especially for the USV, numerous methods have been developed to handle the trajectory tracking control problem including sliding mode control [2], and adaptive backstepping control [3], [4]. Note that the foregoing results assumed that the model dynamics were fully available, which brought some conservative for applying the proposed method to practical applications to a certain extent. To overcome this problem, some intelligent control methods have been proposed to cope with unknown dynamics and nonlinearities by integrating the neural networks or fuzzy logic systems (FLSs) with traditional control methods [5], [6]. However, the above results were focused on the infinite-time stability of the CLSs. To further improve tracking accuracy and convergence rate, some remarkable finite-time control methods have been reported [7]–[10]. In [7], a new super-twisting neural dynamic model was established to achieve adaptive disturbance rejection. In [8], a finite-time disturbance observer was designed to exactly estimate the unknown disturbances. Although better tracking performance for the USV in [8] can be guaranteed in comparison to infinite-time control methods presented in [3]–[6], the determination of the setting time heavily relied on the initial states of the investigated system. This may lead to an overlarge or even inestimable convergence time when the initial states are too far from the equilibrium or fully unpredictable limited by the environment.

More recently, the fixed-time control provides a systematic framework for guaranteeing the convergence time is free of the initial states of the investigated systems. By utilizing this method, some notable results [11]–[18] have been presented for various nonlinear systems. In [14], a fixed-time sliding mode controller was developed to force the attitude of rigid spacecraft into the predefined sliding surface. By integrating with fixed-time stability theory and backstepping control, the adaptive control problems were studied in [16]–[18]. Nevertheless, noted that the derivation of the control law was dependent on the repeated differentiation of virtual control laws in the recursive procedure, which undoubtedly will cause the problems of computational complexity and over parametrization once the dimensionality of the system is too high. Inspired by [9], a novel trajectory tracking control scheme was proposed in [19] by introducing the command filtered backstepping technique. It should be pointed out that the method proposed in [19] is only available for the USV with fully known model dynamics. Moreover, the aforementioned results in [2]–[6], [8], [9], [14]–[19] were based on the time-triggered control scheme, where a large number of network communication resources were required since the control signal need to be updated periodically. Therefore, it is significant to develop an event-triggered adaptive fixed-time trajectory tracking control method for guaranteeing the stability of the CLSs under any initial states and limited network transmission environment.

Motivated by the above discussion and observation, in this brief, we aim to develop an event-triggered adaptive command-filtered practical fixed-time trajectory tracking

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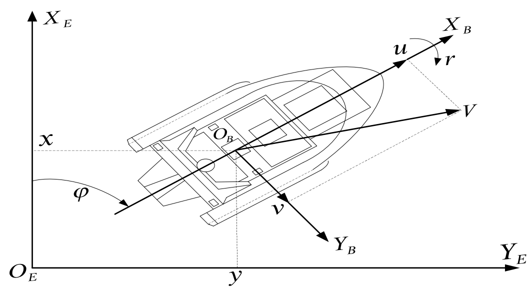

Fig. 1. Earth-fixed $X_E O_E Y_E$ and the body-fixed $X_B O_B Y_B$ coordinate frames.

control scheme for the USV with unknown dynamics. The main contributions of this brief are characterized as follows. (i) This brief makes the first attempts to develop an event-triggered adaptive fuzzy fixed-time trajectory tracking control scheme for the USV with unknown dynamics. What's more, the computational complexity exposed in [16]–[18] is greatly relaxed and the exact inertia dynamics in [19] are not required under the proposed method. (ii) Distinct from [2]–[6], [8], [19], two kinds of compensation signals are constructed for achieving better tracking performance and improving the system robustness against the perturbations, where the negative effects caused by the filter errors, disturbances, and approximation errors are effectively reduced. (iii) Compared with most of open results [2]–[6], [8], [19], the event-triggered mechanism rather than the time-triggered mechanism is introduced to controller design such that the network communication burden is greatly reduced, which is closer to the actual requirements.

II. Problem Formulation

Consider a standard three degrees of freedom (DOF) nonlinear motion model of the USV as shown in Fig. 1. Let $\eta = [x, y, \varphi]^T \in \mathbb{R}^3$ denote the position (x, y) and heading angle φ of the USV in the earth-fixed frame and let $\omega = [u, v, r]^T \in \mathbb{R}^3$ represent the corresponding surge velocity u and sway velocity v, and angular rate r in the body-fixed frame, then a controlled USV dynamic system with unknown dynamics and disturbances can be modeled as follows [22]:

$$\begin{cases} \dot{\eta} = R(\varphi)\omega \\ M\dot{\omega} = -C_m(\omega)\omega - D_m(\omega)\omega + \tau + d(t) \end{cases} \tag{1}$$

where $d(t) = [d_u, d_v, d_r]^T \in \mathbb{R}^3$ denotes the unknown but bounded external disturbances, and $\tau = [\tau_u, \tau_v, \tau_r]^T \in \mathbb{R}^3$ is control input vector. $R(\varphi)$ is the kinematic transformation matrix satisfying the property $R^{-1}(\varphi) = R^T(\varphi)$, $C_m(\omega) \in \mathbb{R}^{3\times 3}$ is an inertial matrix, $C_m(\omega) \in \mathbb{R}^{3\times 3}$ denotes the skew-symmetric matrix of Coriolis and centripetal terms, $D_m(\omega) \in \mathbb{R}^{3\times 3}$ represents the damping matrix.

Remark 1: For model (1), some notable tracking control methods have been presented in [2]–[6], [8]. However, all the aforementioned approaches only guarantee the infinite-time stability or finite-time stability of the USV, where the model dynamics of the USV and the initial states are assumed to be fully available for facilitating controller design and determining the convergence time. Although the exact model requirements were further relaxed in [5], [6], the problem of the explosion of complexity and over parameterization caused by taking derivations repeatedly for control signals restrict its application to some extent. Motivated by these situations, an improved adaptive fixed-time command-filtered trajectory tracking control design for the system (1) with unknown model dynamics will be established.

Control objective: We devote to derive an event-triggered adaptive fixed-time command-filtered trajectory tracking control method for the USV with unknown dynamics such that all the signal of the CLS are bounded, and the tracking errors converge to an arbitrary small neighborhood of the zero in a predefined fixed-time.

Assumption 1: The desired reference signal η_r and its first derivative $\dot{\eta}_r$ are available.

Assumption 2: there exist an unknown constant d_M^{s*} such that $|d_M^s(t)| \le d_M^{s*}$ for all $t \ge 0$, $s = u, v, r$.

III. Main Result

A. Event-Triggered Adaptive Controller Design

In this section, an event-triggered adaptive fixed-time command-filtered trajectory tracking control method for the USV with unknown dynamics will be developed by integrating with the commander filtered backstepping technique and fixed-time stability theory. Firstly, the tracking errors are defined as:

$$\begin{cases} z_1 = \eta - \eta_r, \\ z_2 = \omega - \vartheta_{1,c} \end{cases} \tag{2}$$

where $z_1 \in \mathbb{R}^3$ and $z_2 = [z_{2u}, z_{2v}, z_{2r}]^T$ denote the position tracking error and the velocity tracking error, respectively. $\vartheta_{1,c} \in \mathbb{R}^3$ is the filtered control signal.

Step 1: To overcome the complexity issue existing in the traditional backstepping control method, the following command filter is used to filter the virtual control functions and obtain their differential signals.

$$\begin{aligned} \dot{\lambda}_{1,1} &= \ell_{1,1} \\ \ell_{1,1} &= -\alpha_{1,1}\lceil \lambda_{1,1} - \alpha_1 \rfloor^{\beta_{1,1}} - \alpha_{1,2}\lceil \lambda_{1,1} - \alpha_1 \rfloor^{\beta_{1,2}} + \lambda_{1,2} \\ \dot{\lambda}_{1,2} &= -\alpha_{1,3}\lceil \lambda_{1,1} - \alpha_1 \rfloor^{\beta_{1,3}} - \alpha_{1,4}\lceil \lambda_{1,1} - \alpha_1 \rfloor^{\beta_{1,4}} \end{aligned} \tag{3}$$

where the virtual control function $\alpha_1 \in \mathbb{R}^3$ is the input of the filter, which will be designed. $\vartheta_{1,c} = \lambda_{1,1}$ and $\dot{\vartheta}_{1,c} = \ell_{1,1}$ are the outputs.

Along with (2), the derivative of z_1 is as follow:

$$\dot{z}_1 = R(\varphi)\omega - \dot{\eta}_r \tag{4}$$

Define the filter error $\epsilon_1 = \vartheta_{1,c} - \alpha_1$, then the compensating signal is generated by

$$\dot{\gamma}_1 = -a_1^1\gamma_1 - a_1^2\gamma_1^{\frac{1}{2}} - a_1^3\gamma_1^3 - a_1^4\gamma_1\frac{\epsilon_1^T\epsilon_1}{||\gamma_1||^2} + \epsilon_1, \tag{5}$$

where $a_1^i \in \mathbb{R}^3 (i = 1, 2, \ldots, 4)$ is a positive definite constant matrix to be determined.

Design the virtual control law and adaptive laws as:

$$\alpha_1 = -R^T(\varphi)\left(\frac{\bar{\alpha}_1(z_1^T\bar{\alpha}_1)}{\sqrt{(z_1^T\bar{\alpha}_1)(z_1^T\bar{\alpha}_1) + \varpi_1^2}}\right), \tag{6}$$

$$\bar{\alpha}_1 = k_1^1 z_1 + k_1^2\left(\frac{1}{2}\right)^{\frac{3}{4}} z_1^{\frac{1}{2}} + k_1^3\left(\frac{1}{2}\right)^2 z_1^3 - \dot{\eta}_r, \tag{7}$$

where $k_1^i (i = 1, 2, 3)$ is a positive definite constant matrix.

Select the following Lyapunov function

$$V_1 = \frac{1}{2}z_1^T z_1 + \frac{1}{2}\gamma_1^T\gamma_1 \tag{8}$$

Taking the derivative of V_1 yields

$$\begin{aligned} \dot{V}_1 \le\ & z_1^T(R(\varphi)z_2 + R(\varphi)\epsilon_1 + R(\varphi)\alpha_1 - \dot{\eta}_r) + \gamma_1^T(-a_1^1\gamma_1. \\ & - a_1^2\gamma_1^{\frac{1}{2}} - a_1^3\gamma_1^3 - a_1^4\gamma_1\frac{\epsilon_1^T\epsilon_1}{||\gamma_1||^2} + \epsilon_1), \end{aligned} \tag{9}$$

Utilizing Lemma 4 in [20], the term $z_1^T R(\varphi)\alpha_1$ in (9) can be expressed as

$$z_1^T R(\varphi)\alpha_1 = -\frac{z_1^T\bar{\alpha}_1 z_1^T\bar{\alpha}_1}{\sqrt{z_1^T\bar{\alpha}_1 z_1^T\bar{\alpha}_1 + \varpi_1^2}} \le \varpi_1 - z_1^T\bar{\alpha}_1 \tag{10}$$

Substituting (6)-(7), and (10) into (9), one has

$$\begin{aligned}\dot{V}_1 &\le -\lambda_{min}\{p_1^1, p_1^3\}[(z_1^T z_1/2)^{3/4} + (\gamma_1^T\gamma_1/2)^{3/4}] + z_2^T z_2 \\ &\quad + \varpi_1 - \lambda_{min}\{p_1^2, p_1^4\}[(z_1^T z_1/2)^2 + (\gamma_1^T\gamma_1/2)^2] \qquad (11)\\ &\le -\lambda_{min}\{p_1^1, p_1^3\}V_1^{\frac{3}{4}} - \lambda_{min}\{p_1^2, p_1^4\}V_1^2 + z_2^T z_2 + \varpi_1\end{aligned}$$

where $p_1^1 = k_1^2(2)^{\frac{3}{4}}, p_1^2 = 4k_1^3, p_1^3 = a_1^2(2)^{\frac{3}{4}}$, and $p_1^4 = 4a_1^3$.

Step 2: To facilitate the controller design, the second equation in (1) can be rewritten as:

$$\begin{bmatrix}\dot{u} & \dot{v} & \dot{r}\end{bmatrix}^T = F_M(u, v, r) + \tau_M + d_M(t) \tag{12}$$

where $F_M(u, v, r) = [F_M^u(u, v, r), F_M^v(u, v, r), F_M^r(u, v, r)]^T$, $\tau_M = [\tau_M^u, \tau_M^v, \tau_M^r]^T$, and $d_M(t) = [d_M^u, d_M^v, d_M^r]^T$.

Invoking (2) and (12), the derivative of z_2 can be calculated as:

$$\dot{z}_{2s} = F_M^s(u, v, r) + \tau_M^s(t) + d_M^s - \dot{\vartheta}_{1,c}^s (s = u, v, r), \tag{13}$$

where $\vartheta_{1,c} = [\vartheta_{1,c}^u, \vartheta_{1,c}^v, \vartheta_{1,c}^r]^T$.

Motivated by the work of [21], a relative threshold control strategy is introduced to design the event-triggered adaptive tracking controller. We design the actual control law as:

$$\xi^s(t) = -(1+\delta_s)\frac{z_{2s}\bar{\eta}_{2s}^2}{\sqrt{z_{2s}^2\bar{\eta}_{2s}^2 + \varpi_{2s}^2}} (s = u, v, r) \tag{14}$$

with

$$\begin{aligned}\bar{\eta}_{2s} &= k_2^{1s}z_{2s} + k_2^{2s}(\frac{1}{2})^{\frac{3}{4}}z_{2s}^{\frac{1}{2}} + k_2^{3s}(\frac{1}{2})^2 z_{2s}^3 + \frac{1}{2b_s^2}z_{2s}\hat{\hbar}_s\phi_s^T\phi_s \\ &\quad + \frac{\hat{\Lambda}_s z_{2s}}{\sqrt{z_{2s}^2 + \varrho^2(t)}} + \frac{|z_s\bar{m}_s|}{z_{2s}} - \dot{\vartheta}_{1,c}^s,\end{aligned} \tag{15}$$

and $\forall t \in [t_k, t_{k+1})$, $\tau_M^s(t) (s = u, v, r)$ satisfying

$$\tau_M^s(t) = \xi^s(t_k), \forall t \in [t_k, t_{k+1}) \tag{16}$$

$$t_{k+1} = \inf\{t \in R \,||e_s(t) \ge \delta_s|\tau_M^s(t)| + m_s\} \tag{17}$$

where $e_s(t) = \xi^s(t) - \tau_M^s(t)$ and δ_s, m_s are design parameters satisfying $0 < \delta_s < 1, m_s > 0$.

Remark 2: The role of the term $\hat{\Lambda}_s z_{2s}/\sqrt{z_{2s}^2 + \varrho^2(t)}$ played in (15) is to overcome the negative effects generated by the unknown disturbances and approximation errors. In most existing results, the sign function is usually utilized to achieve the same goal. However, the serious chattering phenomenon and high-gain problem are unavoidable if the upper bound of the unknown disturbances is too big. it worth noting that the undesired phenomenon can be removed by replacing this term with the sign function.

Design the parameter adaptive laws as

$$\dot{\hat{\hbar}}_s = \frac{1}{2b_s^2}z_{2s}^2\phi_s^T\phi_s - \rho_1^s\hat{\hbar}_s - \rho_2^s\hat{\hbar}_s^3, \tag{18}$$

$$\dot{\hat{\Lambda}}_s = \frac{z_{2s}^2}{\sqrt{z_{2s}^2 + \varrho^2(t)}} - \rho_3^s\hat{\Lambda}_s - \rho_4^s\hat{\Lambda}_s^3, \tag{19}$$

where $\rho_i^s > 0 (i = 1, 2, \ldots, 4)$ is a positive constant.

Choose the following Lyapunov function

$$V_2 = \frac{1}{2}\sum_{s=u,v,r} z_{2s}^2 + \frac{1}{2}\sum_{s=u,v,r}\tilde{\hbar}_s^2 + \frac{1}{2}\sum_{s=u,v,r}\tilde{\Lambda}_s^2 \tag{20}$$

where $\tilde{\Lambda}_s = \Lambda_s - \hat{\Lambda}_s$, and $\hat{\Lambda}_s$ is the estimation of $\Lambda_s = d_M^{s*} + \varepsilon_M^{s*}$.

For the interval $[t_k, t_{k+1})$, it follows from (16) and (17) that

$$\xi^s(t) = (1 + \mu_1^s(t)\delta_s)\tau_M^s(t) + \mu_2^s(t)m_s \tag{21}$$

where $\mu_1^s(t)$ and $\mu_2^s(t)$ are the time-varying parameters satisfying $|\mu_1^s(t)| \le 1$ and $|\mu_2^s(t)| \le 1$.

Furthermore, using (21) yields

$$\tau_M^s(t) = \frac{\xi^s(t)}{1 + \mu_1^s(t)\delta_s} - \frac{\mu_2^s(t)m_s}{1 + \mu_1^s(t)\delta_s} \tag{22}$$

According to (21)-(22), the derivative of V_2 is calculated as

$$\begin{aligned}\dot{V}_2 \le &\sum_{s=u,v,r} z_{2s}\Bigg(\frac{\xi^s(t)}{1 + \mu_1^s(t)\delta_s} - \frac{\mu_2^s(t)m_s}{1 + \mu_1^s(t)\delta_s} + \Psi_s + d_M^s \\ &- z_{2s} - \dot{\vartheta}_{1,c}^s\Bigg) - \sum_{s=u,v,r}\tilde{\hbar}_s\dot{\hat{\hbar}}_s - \sum_{s=u,v,r}\tilde{\Lambda}_s\dot{\hat{\Lambda}}_s\end{aligned} \tag{23}$$

where $\Psi_s = F_M^s(u, v, r) + z_{2s}$ with $s = u, v, r$.

Due to the universal approximation ability of FLSs, the FLSs are widely used to handle various nonlinearity encapsulated by unknown dynamics and uncertainties. Thus, the nonlinearity Ψ_s in (23) can be expressed as

$$\Psi_s = \theta_s^T\phi_s(\triangle_s) + \varepsilon_M^s(\triangle_s), \tag{24}$$

in which $\triangle_s = [u, v, r, z_{2s}]^T$ and ε_M^s satisfies $|\varepsilon_M^s| \le \varepsilon_M^{s*}$.

According to (14), we can obtain $z_{2s}\xi^s(t) \le 0 (s = u, v, r)$. Since $\mu_1^s(t) \in [-1, 1]$ and $\mu_2^s(t) \in [-1, 1]$, the following inequalities hold

$$\frac{z_{2s}\xi^s(t)}{1 + \mu_1^s(t)\delta_s} \le \frac{z_{2s}\xi^s(t)}{1 + \delta_s}, \tag{25}$$

$$|\frac{\mu_1^s(t)m_s}{1 + \mu_1^s(t)\delta_s}| \le \frac{m_s}{1 - \delta_s}. \tag{26}$$

Furthermore, we can obtain

$$\begin{aligned}z_{2s}(\Psi_s + d_M^s) \le &\frac{z_{2s}^2\hbar_s\phi_s^T\phi_s}{2b_s^2} + \frac{b_s^2}{2} \\ &+ \Lambda_s\varrho(t) + \frac{\Lambda_s z_{2s}^2}{\sqrt{z_{2s}^2 + \varrho^2(t)}}.\end{aligned} \tag{27}$$

Similar to (10), the term $z_{2s}\tau_M^s$ can be expressed as

$$z_{2s}\xi^s(t) = -\frac{z_{2s}^2\bar{\eta}_{2s}^2}{\sqrt{z_{2s}^2\bar{\eta}_{2s}^2 + \varpi_{2s}^2}} \le \varpi_{2s} - z_{2s}\bar{\eta}_{2s}. \tag{28}$$

Substituting (14)-(19) and (25)-(28) into (23) and using Lemma 2 in [10] gives rise to

$$\begin{aligned}\dot{V}_2 \le &-\sum_{s=u,v,r}(k_2^{1s}+1)z_{2s}^2 - \sum_{s=u,v,r}k_2^{2s}(\frac{z_{2s}^2}{2})^{\frac{3}{4}} \\ &-\sum_{s=u,v,r}k_2^{3s}(\frac{z_{2s}^2}{2})^2 - \sum_{s=u,v,r}\rho_1^s(\frac{1}{2}\tilde{\hbar}_s^2)^{\frac{3}{4}} + \bar{\Upsilon}\end{aligned}$$

$$-\sum_{s=u,v,r}\rho_3^s(\frac{1}{2}\tilde{\Lambda}_s^2)^{\frac{3}{4}}+\sum_{s=u,v,r}\rho_2^s\tilde{\hbar}_s\hat{\hbar}_s^3+\sum_{s=u,v,r}\rho_4^s\tilde{\Lambda}_s\hat{\Lambda}_s^3 \quad (29)$$

where $\bar{\Upsilon}=\frac{1}{2}\sum_{s=u,v,r}[b_s^2+\varpi_{2s}+2\Lambda_s\varrho(t)+\rho_1^s\hbar_s^2+\rho_3^s\Lambda_s^2 2(\rho_1^s+\rho_3^s)(1-\kappa)\iota]$ with $\kappa=\frac{3}{4}, \iota=\kappa^{\frac{\kappa}{1-\kappa}}$.

Furthermore, it follows from the fact $\tilde{\hbar}_s\hat{\hbar}_s^3=\tilde{\hbar}_s(\hbar_s^3-3\hbar_s^2\tilde{\hbar}_s+3\tilde{\hbar}_s^2\hbar_s-\tilde{\hbar}_s^3)$, $\tilde{\Lambda}_s\hat{\Lambda}_s^3=\tilde{\Lambda}_s(\Lambda_s^3-3\Lambda_s^2\tilde{\Lambda}_s+3\tilde{\Lambda}_s^2\Lambda_s-\tilde{\Lambda}_s^3)$ and [Lemma 3-4, 15] that

$$\begin{aligned}\dot{V}_2\leq&-\bar{\Gamma}_1V_2^{\frac{3}{4}}-\frac{\bar{\Gamma}_2}{9}V_2^2-(k_2^{1u}+1)z_{2u}^2-(k_2^{1v}+1)z_{2v}^2\\&-(k_2^{1r}+1)z_{2r}^2+\hat{\Upsilon}_n\end{aligned} \quad (30)$$

where $\hat{\Upsilon}_n=\bar{\Upsilon}_n+\frac{\rho_2^u}{12}\hbar_1^4+\frac{3\rho_2^u}{4\sigma^4}\hbar_1^4+\frac{\rho_2^v}{12}\hbar_2^4+\frac{3\rho_2^v}{4\sigma^4}\hbar_2^4+\frac{\rho_2^r}{12}\hbar_3^4+\frac{3\rho_2^r}{4\sigma^4}\hbar_3^4+\frac{\rho_4^u}{12}\Lambda_1^4+\frac{3\rho_4^u}{4\sigma^4}\Lambda_1^4+\frac{\rho_4^v}{12}\Lambda_2^4+\frac{3\rho_4^v}{4\sigma^4}\Lambda_2^4+\frac{\rho_4^r}{12}\Lambda_3^4+\frac{3\rho_4^r}{4\sigma^4}\Lambda_3^4$, $\bar{\Gamma}_1=\min\{l_1,l_2,l_3\}$ and $\bar{\Gamma}_2=\min\{\frac{l_4}{3},\frac{l_5}{3},\frac{l_6}{3}\}$, $l_1=\min\{k_2^{2u},k_2^{2v},k_2^{2r}\}$, $l_2=\min\{\rho_1^u,\rho_1^v,\rho_1^r\}$, $l_3=\min\{\rho_3^u,\rho_3^r,\rho_3^v\}$ and $l_4=\min\{k_2^{3u},k_2^{3v},k_2^{3r}\}$. $l_5=\min\{(4\rho_2^u-9\rho_2^u\sigma^{\frac{8}{5}}),(4\rho_2^v-9\rho_2^v\sigma^{\frac{8}{5}}),(4\rho_2^r-9\rho_2^r\sigma^{\frac{8}{5}})\}$, $l_6=\min\{(4\rho_4^u-9\rho_4^u\sigma^{\frac{8}{5}}),(4\rho_4^v-9\rho_4^v\sigma^{\frac{8}{5}}),(4\rho_4^r-9\rho_4^r\sigma^{\frac{8}{5}})\}$.

B. Stability Analysis

Theorem 1: For the investigated 3-DOF USV dynamic model (1) under the Assumptions 1-2, if the command filter (3), compensation signal (5), the intermediate control function (6), and the actual control function (14) together with adaptive laws (18)-(19) are employed, then all the signals of the CLS are uniformly bounded within a fixed time and the actual trajectory of the USV can track the arbitrary reference trajectory with an arbitrary small tracking error in fixed-time interval.

Proof: Construct the overall candidate Lyapunov function as

$$V=V_1+V_2 \quad (31)$$

Combining with (11) and (30) lead to

$$\dot{V}\leq-\Gamma_1V^{\frac{3}{4}}-\frac{\Gamma_2}{2}V^2+\Upsilon \quad (32)$$

where $\Upsilon=\hat{\Upsilon}_n+\varpi_1$, $\Gamma_1=\min\{\lambda_{min}\{p_1^1,p_1^3\},\bar{\Gamma}_1\}$, and $\Gamma_2=\min\{\lambda_{min}\{p_1^2,p_1^4\},\frac{\bar{\Gamma}_2}{9}\}$.

It is easily concluded from (32) that $\dot{V}_n\leq-\Gamma_1V_n^{\frac{3}{4}}$ when $V_n^2\geq\frac{2\Upsilon_n}{\Gamma_2}$, from which one gets that V_n is bounded. Furthermore, the boundedness of $z_i,\gamma_1,\tilde{\hbar}_s,\tilde{\Lambda}_s$ can be ensured. It follows from [11, Lemma 1] that the tracking errors can converge to an arbitrary small neighborhood of the origin $|z_{1x}|\leq\sqrt{2\Theta}$ with the predefined convergence time $T_{pf}\leq\frac{4}{\Gamma_1\tau}+\frac{2}{\Gamma_2\tau}$ where $\Theta=\min\{\Gamma_1^{-\frac{4}{3}}(\frac{\Upsilon}{1-\tau})^{\frac{4}{3}},(\frac{\Gamma_2}{2})^{-\frac{1}{2}}(\frac{\Upsilon}{1-\tau})^{\frac{1}{2}}\}$. This completes the proof. ■

Afterwards, we will prove that Zeno behavior can be efficiently avoided by the proposed control scheme. It implies that there exists $t^*>$ such that $t_{k+1}-t_k\geq t^*,\forall k\in Z^+$. Using the definition $e_s(t)=\xi^s(t)-\tau_M^s(t)$, we have $\frac{d}{dt}|e_s|=|\dot{e}_s|sgn(e_s)\leq|\dot{\xi}^s|$. According to (14), one has ξ^s is a differentiable function and $\dot{\xi}^s$ is compounded function of all bounded signals. Therefore, there exists a positive constant b_s such that $|\dot{\xi}^s|\leq b_s$. Furthermore, it follows from $e_s(t_k)=0$ and $\lim_{t\to t_{k+1}}e_s(t)\leq m_s$ that $t^*\geq(\frac{b_s}{m_s})$. Thus, the Zeno behavior can be avoided.

TABLE I
SELECTION OF SIMULATION PARAMETERS

Filter Parameters
$\alpha_{1,i}=\beta_{1,2}=2(i=1,\ldots,4),\beta_{1,1}=0.75,\beta_{1,3}=0.6,$ $\beta_{1,4}=3,a_1^1=diag(2,2,2),a_1^2=diag(0.6,0.6,0.6),$ $a_1^3=diag(0.8,0.8,0.8),a_1^4=diag(1.2,1.2,1.2),$
Controller Parameters
$k_1^1=2.5k_1^2=diag(5,5,5),k_1^3=diag(3,3,3),$ $k_2^{1s}=50,k_2^{2s}=k_2^{2s}=10,\delta_s=0.5,m_s=0.02,$ $b_s=0.01,\varpi_{2s}=0.1(s=u,v,r),\varrho(t)=e^{-10t}.$
Initial Conditions
$[x(0),y(0),\varphi(0)]=[1m,1m,\frac{\pi}{4}],\hat{\hbar}_s(0)=0.5,$ $\hat{\Lambda}_s(0)=0.3,[u(0),v(0),r(0)]=[0,0,0]^T.$
Reference Trajectory
$x_r=4\sin(0.02t);y_r=2.5(1-\cos(0.02t));\varphi_r=0.02t$
External Disturbances
$d(t)=[5\sin(t),5\sin(t),5\sin(t)]^T$

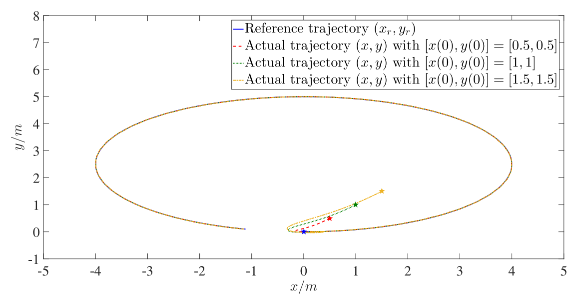

Fig. 2. Desired and actual trajectories in *xy* plane under the different initial conditions.

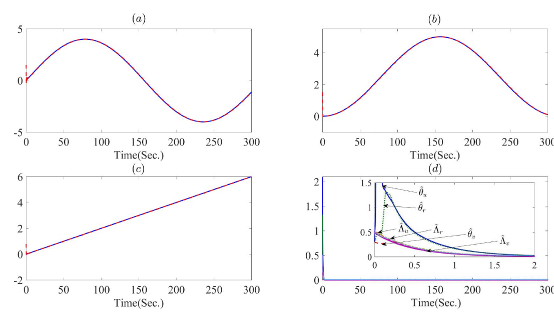

Fig. 3. Response of the CLS. (a)-(b) Desired and actual positions. (c) Desired and actual yaw angles. (d) Adaptive parameters.

IV. SIMULATION RESULT

To verify the validity of the proposed control method, the simulation study is carried out on Cybership II in this section, which is a 1 : 70 scale replica of a supply ship of the Marine Cybernetics Laboratory in Norwegian University of Science and Technology, and the detailed system parameters of the ship are provided in [22].

The control parameters, initial conditions, and external disturbances are provided in Table I. and the Gaussian membership functions of the FLSs are chosen as $\mu_{F_s^i}(\Delta_s)=\exp[-(\Delta_s-i+5)^2/4)]$, $(s=u,v,r;i=1,2,\ldots,9)$ where $\Delta_s=[u,v,r,z_{2s}]^T$.

The simulation results are presented in Fig. 2-Fig. 5. Fig. 2 displays the response curves of desired and actual trajectories in the $x-y$ plane under different initial conditions. It is demonstrated that the convergence of the CLS is not dependent on the initial system states in contrary to infinite-time control and finite-time control. Fig. 3 depicts the curves of desired and

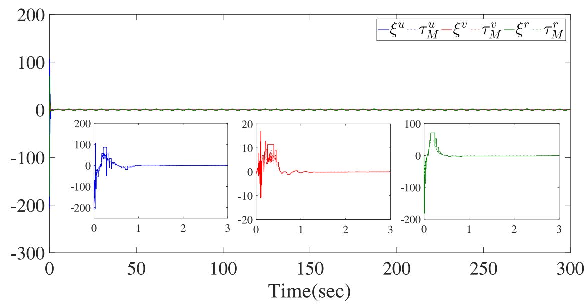

Fig. 4. Control inputs.

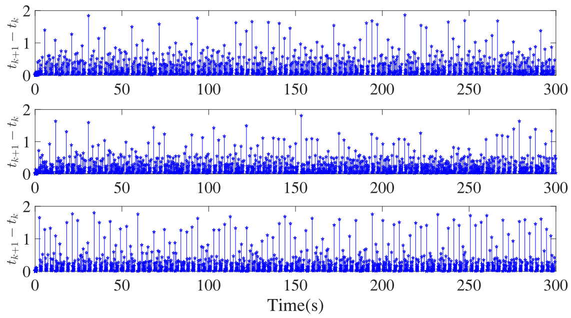

Fig. 5. Released interval of triggering events.

actual positions, yaw angles and adaptive parameters $\hat{\theta}_s$, $\hat{\Lambda}_s$, which indicates the predefined control goal can be achieved with an exact tracking accuracy and rapid convergence speed under the proposed control method. The response of control signals ξ^s and τ_M^s is presented in Fig. 4. The time intervals of events are displayed in Fig. 5 and it is easily calculated that the number of triggers for all actuators is 1269 times, 1479 times, and 1621 times in 300s while the number of non-triggering events is 33341 times, 33131 times, and 32989 times, which means the proposed method can greatly save the communication resources and decrease the control cost in comparison to the time-triggered control scheme proposed in [2]–[6], [8], [9], [14]–[19].

Remark 3: Finally, it should be pointed out that the selection of design parameters have a great influence on tracking performance. For example, the tracking performance is improved by increasing the value of design parameters $k_i^{js}(i = 1, 2; j = 1, 2, 3)$. However, this will lead to overlarge control energy. Therefore, in practice, to keep a balance between tracking performance and control cost, the appropriate choice of the design parameters is significant.

V. Conclusion

In this brief, a novel event-triggered adaptive command-filtered fixed-time trajectory tracking control scheme for the USV has been proposed. By using the proposed control strategy, the computational complexity and network communication burden are greatly reduced and the serious dependencies on the exact model dynamics and initial conditions of the vehicle are further relaxed compared with most of the existing results. The simulation results prove that the proposed method is able to guarantee a desired tracking performance. Here, it worth noting that the proposed control method in this brief could be further extended to deal with the tracking control problem of aircraft system studied in [23] and safety analysis studied in [24]. Besides, developing a disturbance observer-based adaptive global fixed-time trajectory tracking control for the USV to achieve better disturbance rejection will be one of our further research works.

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