Letter

Safety-Critical Model-Free Control for Multi-Target Tracking of USVs with Collision Avoidance

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Dear editor,

This letter addresses the multi-target tracking of underactuated unmanned surface vehicles (USVs) subject to multiple stationary/moving obstacles. The kinetic model parameters of each USV are totally unknown. A safety-critical model-free control method is proposed for tracking multiple targets with a collision-free containment formation. Specifically, a distributed containment extended state observer (DCESO) is designed to estimate the convex hull spanned by the multiple targets. At the kinematic level, a collision-free kinematic guidance law is presented using a control barrier function (CBF) and an extended state observer for each follower USV. At the kinetic level, a model-free position tracking control law by using an adaptive ESO (AESO) is presented for each follower USV. By the designed safety-critical model-free control method, cooperative tracking of multiple targets under multiple stationary/moving obstacles can be achieved using completely unknown kinetic model parameters. Simulations are provided to illustrate the efficacy of the proposed safety-critical model-free control method for a fleet of USVs.

Related work: As an important tool for developing and protecting the ocean, marine vehicles are widely used in military and civil fields such as situation awareness of offshore areas, environmental monitoring, and cooperative rescue [1]−[6]. For diversified oceanic missions, different motion scenarios have been studied in recent years [7], including cooperative trajectory tracking, cooperative path following [1], cooperative target enclosing [8], and cooperative target tracking [9]. More specifically, cooperative target tracking is to force a swarm of follower marine vehicles to track one/multiple target vehicles.

Recently, target tracking of marine surface vehicles has aroused word-wide interest [9]−[12]. In [10] and [11], one follower vehicle can track one target vehicle subject to the unavailable target velocity. In [9], [12], a fleet of follower vehicles can track one target vehicle under the unavailable target velocity. However, the target tracking control methods in [9]−[12] can only achieve that one follower vehicle/multiple follower vehicles track one target. This will limit the autonomy level of USVs [13]. Besides, the target tracking control methods in [9]−[11] can not guarantee the collision free tracking. This may cause a failure of cooperative control [14]. Addition, the target tracking control methods in [9]−[12] assume that the kinetic vehicle model is a prior model. Nevertheless, the prior model is obtained from a large number of experiments. Besides, the prior model may suffer from variations in practical applications due to load change, actuator faults, or additive nonlinear disturbances induced by environmental circumstances [15]. More practically, it is highly desirable to design a model-free control method for USVs without a prior kinetic model.

In this letter, we aim to address the multi-target tracking of USVs subject to multiple stationary/moving obstacles, in addition to completely unknown kinetic model parameters. By using a DCESO to estimate the convex hull spanned by the multiple targets. A collision-free kinematic guidance law is designed for each follower USV using a CBF and an ESO at the kinematic level. Besides, the developed kinematic guidance law only uses the relative range and angle, which can be obtained by local sensors. At the kinetic level, a model-free position tracking control law using an AESO is designed for each follower USV. The contribution of the proposed control method is threefold. Firstly, the autonomy level of USVs is enhanced by achieving multiple follower USVs to track multi-target. Secondly, the CBFs are embedded into the guidance laws such that the USVs will not collide with stationary/moving obstacles and other USVs. Finally, the cooperative target tracking can be obtained without a prior kinetic model.

Problem statement: Consider a coordinated control system consisting of N follower USVs and M leader vehicles. The dynamic equation of the ith follower USV can be described as

$$\begin{cases} \dot{p}_i = \begin{bmatrix} \cos(\psi_i) & -\sin(\psi_i) \\ \sin(\psi_i) & \cos(\psi_i) \end{bmatrix} \begin{bmatrix} u_i \\ v_i \end{bmatrix} \\ \dot{\psi}_i = r_i \\ \dot{u}_i = f_{ui}(u_i, v_i, r_i) + b_{ui}\tau_{ui} + d_{ui} \\ \dot{v}_i = f_{vi}(u_i, v_i, r_i) + d_{vi} \\ \dot{r}_i = f_{ri}(u_i, v_i, r_i) + b_{ri}\tau_{ri} + d_{ri} \end{cases} \tag{1}$$

where $i = 1,\ldots,N$; $p_i = [x_i, y_i]^T$ and ψ_i are the position and heading angle of the ith follower as shown in Fig. 1; u_i, v_i, and r_i represent the surge velocity, sway velocity and angular rate of the ith follower; f_{ui}, f_{vi}, and f_{ri} represent the uncertain nonlinearities including unmodeled hydrodynamics, hydrodynamic damping forces, and Coriolis forces; b_{ui} and b_{ri} denote the mass parameter; τ_{ui} and τ_{ui} denote the control input; d_{ui}, d_{vi}, and d_{ri} denote the disturbance caused by wind, waves and ocean currents.

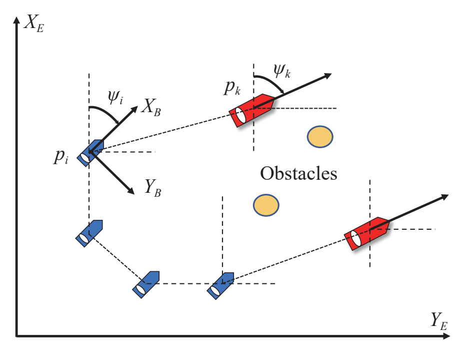

Fig. 1. The geometrical illustration of safety-critical model-free control.

The N USVs are supposed to track M target vehicles and their positions are denoted by $p_k = [x_k, y_k]^T$ with $k = N+1, N+2, \ldots, N+M$.

Assumption 1: For each follower USV, there is at least one target that can access to the follower USV.

The control objective of this letter is to design a safety-critical model-free control law for a fleet of follower USVs with dynamics (1) to track multiple target vehicles under multiple stationary/moving obstacles.

Basic concept: Consider a system as $\dot{x} = f(x) + g(x)u$, where $x \in \mathbb{R}^N$ is the state, $u \in \mathbb{R}^M$ is the input, $f(x): \mathbb{R}^N \to \mathbb{R}^N$, and $g(x): \mathbb{R}^N \to \mathbb{R}^{N\times M}$. Let $\mathcal{S} \subset \mathcal{F} \subset \mathbb{R}^N$ as the superlevel set of $h(x): \mathbb{R}^N \to \mathbb{R}$, $S = \{x \in \mathbb{R}^N | h(x) \geq 0\}$, $\partial S = \{x \in \mathbb{R}^N | h(x) = 0\}$ and $\mathrm{Int}(S) = \{x \in \mathbb{R}^N | h(x) > 0\}$. If h is a CBF, and the inequality $\dot{h}(x) + \kappa h(x) \geq 0$,

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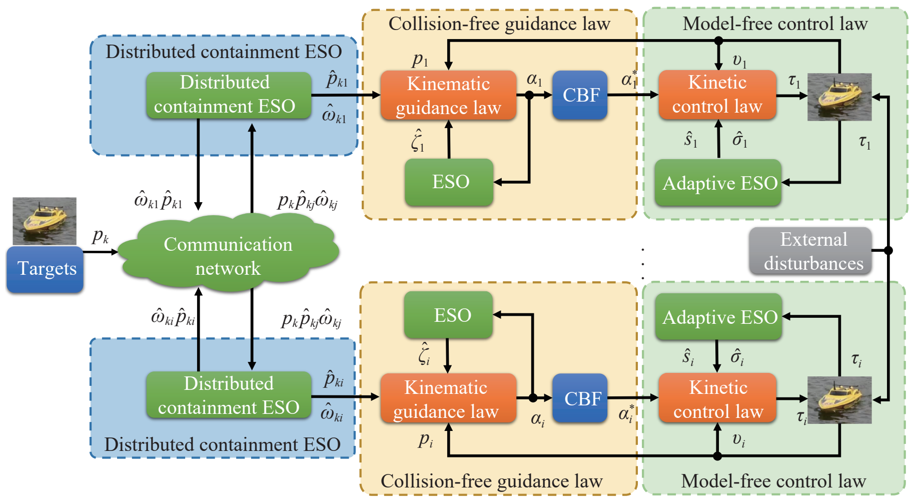

Fig. 2. The safety-critical model-free control architecture.

$\forall x \in \mathcal{F}$ holds where $\dot{h}(x) = \nabla h(f(x)+g(x)u)$ and $\kappa \in \mathbb{R}^+$.

Design and analysis: Model-free control architecture for tracking multiple targets is shown in Fig. 2.

Distributed containment ESO: In this letter, the cooperative target tracking problem is addressed by a design of DCESO for followers to infer the convex hull spanned by the targets. The DCESO is designed as

$$\begin{cases} \dot{\hat{p}}_{ki} = -ck_{pi}\Big(\sum_{j=1}^{N} a_{ij}(\hat{p}_{ki}-\hat{p}_{kj}) + \sum_{k=N+1}^{N+M} b_i^k(\hat{p}_{ki}-p_k)\Big) + \hat{\omega}_{ki} \\ \dot{\hat{\omega}}_{ki} = -ck_{\omega i}\Big(\sum_{j=1}^{N} a_{ij}(\hat{p}_{ki}-\hat{p}_{kj}) + \sum_{k=N+1}^{N+M} b_i^k(\hat{p}_{ki}-p_k)\Big) \end{cases} \tag{2}$$

where $\hat{p}_{ki} = [\hat{x}_{ki}, \hat{y}_{ki}]^T$ and $\hat{\omega}_{ki} = [\hat{u}_{ki}, \hat{v}_{ki}]^T$ are the observer states of the ith virtual point of the convex hull spanned by the leaders. Let b_i^k be the communication between the ith virtual point and kth target, $k_{pi} \in \mathbb{R}^+$, $k_{\omega i} \in \mathbb{R}^+$, and $c \in \mathbb{R}^+$. Let $\tilde{p}_{ki} = \hat{p}_{ki} - p_k$, $\tilde{\omega}_{ki} = \hat{\omega}_{ki} - \dot{p}_k$, $\xi_i = [\tilde{p}_{ki}^T, \tilde{\omega}_{ki}^T]^T$, and $\xi = [\xi_1^T, \ldots, \xi_N^T]^T$, and the dynamics of the ξ is given

$$\dot{\xi} = (I_N \otimes A - c\mathcal{H} \otimes FC)\xi_i - I_N \otimes (B\ddot{p}_k) \tag{3}$$

where $A_i = [0_2, I_2; 0_2, 0_2]^T$, $A = \mathrm{diag}\{A_1, \ldots, A_N\}$, $B_i = [0_2, I_2]^T$, $B = \mathrm{diag}\{B_1, \ldots, B_N\}$, $C_i = [I_2, 0_2]^T$, $C = \mathrm{diag}\{C_1, \ldots, C_N\}$, $F_i = [k_{pi}, k_{\omega i}]^T$, $F = \mathrm{diag}\{F_1, \ldots, F_N\}$, and $\mathcal{H} = \mathcal{L} + \mathcal{B}_k$ with $\mathcal{B}_k = \mathrm{diag}\left\{b_i^k\right\}$, as the targets adjacency matrix. From Lemma 1 in [16], we can get that $\mathcal{L}$ is the Laplacian matrix and $q = [q_1, \ldots, q_N]^T = \mathcal{H}^{-1} 1_N$, $Z = \mathrm{diag}\{z_i\} = \mathrm{diag}\{1/q_i\}$ $(i = 1, \ldots, N)$, and $G = Z\mathcal{H} + \mathcal{H}^{-1}Z$. Suppose that there exist two positive definite matrices P and Q such that $A^TP + PA - PC^TCP \le -Q$.

Lemma 1: Consider the DCESO (2) with $F = PC^T$ and $c > 1/\min_{i=1,\ldots,N}\{q_i g_i\}$. Under Assumption 1, the subsystem (3): $[\ddot{p}_k] \mapsto [\xi_i]$ is input-to-state stable (ISS).

Proof: Construct a Lyapunov function for error dynamics (3) as $V_{\xi_i} = (1/2)\xi_i^T(Z \otimes P)\xi_i$. The derivative of V_{ξ_i} is $\dot{V}_{\xi} = \sum_{i=1}^{N}((1/2)z_i\varrho_i^T \times ((A_i^TP_i + P_iA_i) - cq_ig_iP_iC_i^TC_iP_i)\varrho_i - z_i\varrho_i^T(P_iB_i\ddot{p}_k))$ where $\varrho_i = (U^T \otimes I_N)\xi_i$ is a state transformation can be found in [17]. Therefore, one can see that $\dot{V}_{\xi} \le -\frac{1}{2}\min_{i=1,\ldots,N}\{z_i\}\lambda_{\min}(Q)\,(1-\theta_1)\|\bar{\xi}\|^2$ as long as $\|\varrho_i\| \ge 2\|PB\|\|\ddot{p}_k\|/\theta_1\lambda_{\min}(Q)$, where $\theta_1 \in (0,1)$. Thus, it is concluded that the DCESO (2) is ISS. ∎

Collision-free guidance law: Define $p_{di} = [x_{di}, y_{di}]$ as the desired deviation between the ith reference point and the ith follower. The relative range ρ_i and angle β_i between the ith follower USV and the ith virtual point are obtained $\rho_i = \sqrt{(\hat{y}_{ki} - y_i - y_{di})^2 + (\hat{x}_{ki} - x_i - x_{di})^2}$ and $\beta_i = \mathrm{atan2}(\hat{y}_{ki} - y_i - y_{di}, \hat{x}_{ki} - x_i - x_{di})$. The tracking errors are defined as

$$e_{\rho i} = \rho_i - \rho_{di}, \quad e_{\beta i} = \beta_i - \psi_i \tag{4}$$

where ρ_{di} is the desired distance between the ith reference point and the ith follower USV. The dynamics of $e_{\rho i}$ and $e_{\beta i}$ is $\dot{e}_{\chi i} = [\dot{e}_{\rho i}, \dot{e}_{\beta i}]^T$, and $\alpha_i = [\alpha_{ui}, \alpha_{ri}]^T$ is the guidance law to be designed in the following, $\zeta_i = [\zeta_{ui}, \zeta_{ri}]^T = [\hat{u}_{ki}\cos(\beta_i) + \hat{v}_{ki}\sin(\beta_i) - \dot{l}_i - u_i + \alpha_{ui} - v_i\sin(\beta_i - \psi_i) + 2u_i\sin^2((\beta_i - \psi_i)/2),\ \ (1/\rho)_i(-\hat{u}_{ki}\sin(\beta_i) - \dot{\theta} + \hat{v}_{ki}(\beta_i) - v_i\cos(\beta_i - \psi_i) + u_i\sin(\beta_i - \psi_i) - r_i + \alpha_{ri}]^T$. The function ζ_i is unavailable because of unknown sway velocity v_i. To recover ζ_i, an ESO at the kinematic level is proposed

$$\begin{cases} \dot{\hat{e}}_{\chi i} = -k_{ei}\left(\hat{e}_{\chi i} - e_{\chi i}\right) + \hat{\zeta}_i - \alpha_i \\ \dot{\hat{\zeta}}_i = -k_{\zeta i}\left(\hat{e}_{\chi i} - e_{\chi i}\right). \end{cases} \tag{5}$$

Assumption 2: For unknown function ζ_i, there is $\zeta_i^* \in \mathbb{R}^+$, such that $\|\dot{\zeta}_i\| \le \zeta_i^*$.

Define $\tilde{e}_{\chi i} = \hat{e}_{\chi i} - e_{\chi i}$ and $\tilde{\zeta}_i = \hat{\zeta}_i - \zeta_i$, and it follows from (5) that:

$$\dot{\tilde{e}}_{\chi i} = -k_{ei}\tilde{e}_{\chi i} + \tilde{\zeta}_i, \dot{\tilde{\zeta}}_i = -k_{\zeta i}\tilde{e}_{\chi i} - \dot{\zeta}_i. \tag{6}$$

To stabilize $e_{\chi i}$, a guidance law based on the ESO is given as

$$\alpha_i = k_{\alpha i} e_{\chi i} + \hat{\zeta} \tag{7}$$

where $k_{\alpha i} \in \mathbb{R}^2$. To achieve collision-free control, the inequalities $\|p_i - p_{io}\|^2 - \mu_{io}\|\psi_i - ((\pi/2) + \beta_{io})\|^2 \ge \rho_{io}^2$, and $\|p_i - p_j\|^2 - \mu_{ij}\|\psi_i - ((\pi/2) + \beta_{ij})\|^2 \ge \rho_{ij}^2$ hold, where $p_i = [x_i, y_i]^T$ is the position of the ith follower and $p_{io} = [x_{io}, y_{io}]^T$ is the position of the ith stationary/moving obstacle. For the static obstacle, $\dot{p}_{io} = 0$, and for the moving obstacle, $\dot{p}_{io} \ne 0$. ρ_{io} and ρ_{ij} are the desired obstacle avoidance distance and the USVs avoidance distance respectively. $\beta_{io} = \mathrm{atan2}(y_{io} - y_i, x_{io} - x_i)/\beta_{ij} = \mathrm{atan2}(y_j - y_i, x_j - x_i)$ is the angle between the ith USV and the ith obstacle/jth USV, and $\mu_{io} \in \mathbb{R}^+$ and $\mu_{ij} \in \mathbb{R}^+$. According to the definition of the CBF, the function h_{io} and h_{ij} are defined $h_{io} = \|p_i - p_{io}\|^2 - \mu_{io}\|\psi_i - ((\pi/2) + \beta_{io})\|^2 - \rho_{io}^2$ and $h_{ij} = \|p_i - p_j\|^2 - \mu_{ij}\|\psi_i - ((\pi/2) + \beta_{ij})\|^2 - \rho_{ij}^2$, with $\nabla h_{io} = 2(x_i - x_{io}) + 2(y_i - y_{io}) - 2\mu_{io}(\psi_i - ((\pi/2) + \beta_{io}))$ and $\nabla h_{ij} = 2(x_i - x_j) + 2(y_i - y_j) - 2\mu_{ij}(\psi_i - ((\pi/2) + \beta_{ij}))$.

Then, the collision-free guidance law α_{ri}^* is obtained by the following quadratic programming problem:

$$\arg\min_{\alpha_{ri}^* \in \mathbb{R}} J_i\left(\alpha_{ri}^*\right) = \|\alpha_{ri}^* - \alpha_{ri}\|^2$$
$$\text{s.t. } \nabla h_{iw}\alpha_{ri}^* = -k_{iw}h_{iw} \tag{8}$$

where $k_{iw} \in \mathbb{R}^+$ and w denotes o and j. The safe set $\mathcal{S}$ is defined as $\mathcal{S} = \{p \in \mathbb{R} | h_{iw} \ge 0\}$, here $h_{iw}: \exists C_{iw} \in \mathbb{R}^+$ such that $\|\nabla h_{iw}\| \le C_{iw}$, $\forall p \in \mathcal{S}$, $\nabla h_{iw} \ne 0$.

Model-free control law: At the kinetic level, to achieve collision-free track, define the velocity tracking error as

$$e_{vi} = v_i - \alpha_i^* \tag{9}$$

where $e_{vi} = [e_{ui}, e_{ri}]^T$, $v_i = [u_i, r_i]^T$, $\alpha_i^* = [\alpha_{ui}, \alpha_{ri}^*]^T$. It follows from

(1) that the dynamics of e_{vi} is $\dot{e}_{vi}=s_i+b_{vi}\tau_{vi}=\sigma_i+\hat{b}_{vi}\tau_{vi}$, and $b_{vi}=\mathrm{diag}\{b_{ui},b_{ri}\}$, $\tau_{vi}=[\tau_{ui},\tau_{ri}]^T$, $s_i=[f_{ui},f_{ri}]^T-[\alpha_{ui},\alpha^*_{ri}]^T+[d_{ui},d_{ri}]^T$, $\sigma_i=s_i+b_{vi}\tau_{vi}-\hat{b}_{vi}\tau_{vi}$, and $\hat{b}_{vi}$ is the estimate of b_{vi}. The kinetic model satisfies the ultra-local model [18]. Since s_i, σ_i, and b_{vi} are totally unknown, and the presented control method is model-free [18]. To estimate unknown functions s_i and σ_i, and mass parameter b_{vi}, an AESO is proposed as follows:

$$\begin{cases}\dot{\hat{e}}_{vi}=-k_{vi}(\hat{e}_{vi}-e_{vi})+\hat{\sigma}_i+\hat{b}_{vi}\tau_{vi}\\ \dot{\hat{\sigma}}_i=-k_{\sigma i}(\hat{e}_{vi}-e_{vi})\\ \dot{\hat{s}}_i=\Gamma_{si}\mathrm{Proj}\{\hat{s}_i,\hat{\sigma}_i-\hat{s}_i\}\\ \dot{\hat{b}}_{vi}=\Gamma_{bi}\mathrm{Proj}\{\hat{b}_{vi},\tau^T_{vi}(\hat{\sigma}_i-\hat{s}_i)\}\end{cases} \tag{10}$$

where $\mathrm{Proj}(\cdot)$ is the projection operator, and Γ_{si} and Γ_{bi} are positive constants. Define $\tilde{e}_{vi}=\hat{e}_{vi}-e_{vi}$ $\tilde{s}_i=\hat{s}_i-s_i$, $\tilde{\sigma}_i=\hat{\sigma}_i-\sigma_i$, and $\tilde{b}_{vi}=\hat{b}_{vi}-b_{vi}$, and it can be obtained $\hat{\sigma}_i-\hat{b}_{vi}=-\tilde{s}_i-\tilde{b}_{vi}\tau_{vi}+\varepsilon_i$ with ε_i being the reconstruct error and

$$\begin{cases}\dot{\tilde{e}}_{vi}=-k_{vi}\tilde{e}_{vi}+\tilde{\sigma}_i\\ \dot{\tilde{\sigma}}_i=-k_{\sigma i}\tilde{e}_{vi}-\dot{\sigma}_i\\ \dot{\tilde{s}}_i=\Gamma_{si}\mathrm{Proj}\{\hat{s}_i,\hat{\sigma}_i-\hat{s}_i\}-\dot{s}_i\\ \dot{\tilde{b}}_{vi}=\Gamma_{bi}\mathrm{Proj}\{\hat{b}_{vi},\tau^T_{vi}(\hat{\sigma}_i-\hat{s}_i)\}-\dot{b}_{vi}.\end{cases} \tag{11}$$

Assumption 3: For unknown functions s_i, σ_i, and ship mass b_{vi}, there exist $s^*_i\in\mathbb{R}^+$, $\sigma^*_i\in\mathbb{R}^+$, and $b^*_{vi}\in\mathbb{R}^+$ such that $\|\dot{s}_i\|\le s^*_i$, $\|\dot{\sigma}_i\|\le\sigma^*_i$, and $|\dot{b}_{vi}|\le b^*_{vi}$.

To stabilize e_{vi}, the model-free control law for target tracking is proposed

$$\tau_{vi}=\frac{-k_{vi}e_{vi}-\hat{\sigma}_i}{\hat{b}_{vi}} \tag{12}$$

where $k_{vi}\in\mathbb{R}^2$ is a control law parameter vector.

Main results:

Lemma 2: Under Assumption 2, the ESO subsystem (6): $[\dot{\zeta}_i]\mapsto[\tilde{\zeta}_i,\tilde{e}_{\chi i}]$ is ISS.

Proof: It follows from ESO (5) that the dynamics of the $\tilde{e}_{\chi i}$ and $\tilde{\zeta}_i$ is rewritten as $\dot{\tilde{\phi}}_i=A_{\phi i}\tilde{\phi}_i-\dot{\zeta}_{\phi i}$, where $\tilde{\phi}_i=[\tilde{e}_{\chi i},\tilde{\zeta}_i]^T$, $A_{\phi i}=[-k_{ei},1;-k_{\zeta i},0]$, and $\dot{\zeta}_{\phi i}=[0,\dot{\zeta}_i]^T$. $A_{\phi i}$ is Hurwitz, and there exists a unique positive definite matrix $P_{\phi i}$, such that $A^T_{\phi i}P_{\phi i}+P^T_{\phi i}A_{\phi i}=-I$. Construct the Lyapunov function as $V_{\phi i}=(1/2)\tilde{\phi}^T_iP_{\phi i}\tilde{\phi}_i$. The dynamics of $V_{\phi i}$ is $\dot{V}_{\phi i}=\tilde{\phi}^T_i(A^T_{\phi i}P_{\phi i}+P^T_{\phi i}A_{\phi i})\tilde{\phi}_i+\tilde{\phi}^T_iP_{\phi i}(-\dot{\zeta}_{\phi i})\le-\|\tilde{\phi}_i\|^2+\|\tilde{\phi}_i\|\|P_{\phi i}\|\|\dot{\zeta}_{\phi i}\|$. Note that as $\|\tilde{\phi}_i\|\ge(\|P_{\phi i}\|\|\dot{\zeta}_{\phi i}\|)/a_1$, $\dot{V}_{\phi i}\le-(1-a_1)\|\tilde{\phi}_i\|^2$ with $a_1\in(0,1)$. ■

Lemma 3: Under Assumption 3, the AESO subsystem (11): $[\dot{\sigma}_i]\mapsto[\tilde{e}_{vi},\tilde{\sigma}_i]$ is ISS.

Proof: Construct the Lyapunov function as $V_{si}=(1/2)(\tilde{s}^T_i\Gamma^{-1}_{si}\tilde{s}_i+\tilde{b}^T_{vi}\Gamma^{-1}_{bi}\tilde{b}_{vi})$, and the time derivatives of V_{si} is $\dot{V}_{si}\le-\tilde{s}^2_i-2\tilde{s}_i\tilde{b}_{vi}\tau_{vi}-\tilde{b}^2_{vi}\tau^2_{vi}-\tilde{b}_{vi}\tau_{vi}\varepsilon_i+\Gamma^{-1}_{si}\tilde{s}_is^*_i\le-\|\epsilon_i\|^2+\|\iota_i\|\|\epsilon_i\|$ where $\epsilon_i=\tilde{s}_i+\tilde{b}_{vi}\tau_{vi}$ and $\iota_i=\max\{\varepsilon_i,\Gamma^{-1}_{si}s^*_i\}$. Note that as $\|\epsilon_i\|\ge\|\iota_i\|/a_2$, $\dot{V}_{si}\le-(1-a_2)\|\epsilon_i\|^2$ with $a_2\in(0,1)$. It is concluded that the error ϵ_i is bounded. Then, the proof of the first part $[\dot{\tilde{e}}_{vi},\dot{\tilde{\sigma}}_i]^T$ in equation (11) is similar to Lemma 2, which is omitted here. ■

Lemma 4: The tracking error subsystem consisting of (4) and (9): $[\tilde{\zeta},\tilde{\sigma}_i,\epsilon_i]\mapsto[e_{\chi i},e_{vi}]$ is ISS.

Proof: Construct the Lyapunov function as $V_{ei}=V_{\chi i}+V_{vi}=\sqrt{(1/2)\mathrm{e}^T_{\chi i}e_{\chi i}}+\sqrt{(1/2)\mathrm{e}^T_{vi}e_{vi}}$, and the time derivative of V_{ei} is

$$\begin{aligned}\dot{V}_{ei}&=-k_{ei}e^2_{\chi i}-f_i-k_{vi}e^2_{vi}-e_{vi}\tilde{\sigma}_i+e_{vi}\left(-\tilde{s}_i-\tilde{b}_{vi}\tau_{vi}+\varepsilon_i\right)\\ &\le\frac{1}{\sqrt{2\mathrm{e}^T_{\chi i}e_{\chi i}}}(-\lambda_{\min}(k_{\alpha i})\|e_{\chi i}\|^2+\|e_{\chi i}\|\,\|\tilde{\zeta}_i\|)\\ &\quad+\frac{1}{\sqrt{2\mathrm{e}^T_{vi}e_{vi}}}(-\lambda_{\min}(k_{vi})\|e_{vi}\|^2+\|e_{vi}\|\,\|\tilde{\sigma}_i\|)\\ &\le-k_{\min}V_{ei}+\frac{1}{\sqrt{2}}(\|\tilde{\zeta}_i\|+\|\tilde{\sigma}_i\|)\end{aligned} \tag{13}$$

where $k_{\min}=\min\{\lambda_{\min}(k_{\alpha i}),\lambda_{\min}(k_{vi})\}$.

Theorem 1: Consider the follower USVs (1), the DCESO (2), the ESO (5), the collision-free guidance law (8), the AESO (10), and the model-free control law (12). Under Assumptions 1–3, if $\lambda_{\min}(k_{ei})>\max\{\kappa_{io},\kappa_{ij}\}$, the entire closed-loop safety-critical model-free control system is input-to-state safe such that $(p_0,e_{v0})\in\mathcal{C}\Rightarrow p(t)\in\mathcal{S}$, $\forall t\ge0$, where $\mathcal{C}=\{(p,e_{vi})\in\mathbb{R}\times\mathbb{R}^N:\hbar_{iw}(p,e_{vi})\ge0\}$, with $\hbar_{iw}(p,e_{vi})=k^e_{iw}h(p)-V_{vi}(p,e_{vi})+k^e_{iw}\iota_{iw}(\|\tilde{\sigma}_i\|_\infty)/\sqrt{2}k_{iw}$, and $k^e_{iw}=(\lambda_{\min}(k_{ei})-k_{iw})/\sqrt{2}C_{iw}>0$.

Proof: Lemma 2 shows that the subsystem (6) with states $\tilde{e}_{\chi i}$ and $\tilde{\zeta}_i$ and input $\dot{\zeta}_i$ is ISS; Lemma 3 shows that the subsystem (11) with states $\tilde{e}_{vi}$ and $\tilde{\sigma}_i$ and input $\dot{\sigma}_i$ is ISS; Lemma 4 shows that the subsystem consists of (4), and (9) with states $e_{\chi i}$ and e_{vi} and inputs $\tilde{\zeta}$, $\tilde{\sigma}_i$, and ϵ_i is ISS. By cascade stability analysis, it is proven that the entire closed-loop subsystem consists of (6), (11), (4), and (9) with states $\tilde{e}_{\chi i}$, $\tilde{e}_{vi}$, $e_{\chi i}$ and e_{vi} and inputs $\dot{\zeta}_i$, $\dot{\sigma}_i$, and ϵ_i is ISS. Since $(p_0,e_{v0})\in\mathcal{C}$ and $\dot{\hbar}_{iw}(p,e_{vi})\ge\lambda_{\min}(k_{ei})V_{vi}-1/\sqrt{2}(\|\tilde{\sigma}_i\|_\infty)-k_{iw}\hbar_{iw}-k_{iw}V_{vi}+1/\sqrt{2}(\|\tilde{\sigma}_i\|_\infty)-k^e_{iw}\|\nabla h_{iw}\|\|e_{vi}\|\ge(-k_{iw}-\lambda_{\min}(k_{vi}))V_{vi}-k^e_{iw}\|\nabla h_{iw}\|\|e_{vi}\|\ge-k_{iw}\hbar_{iw}$. It is concluded that $p(t)\in\mathcal{S}$, $\forall t\ge0$, and $\hbar_{iw}>0$. Therefore, the entire closed-loop system is input-to-state safe. ■

Simulations: The model parameters of the USVs are taken from [19]. The control parameters are chosen as: $k_{pi}=10$, $k_{\omega i}=10$, c$=1$, $k_{ei}=10$, $k_{\zeta i}=100$, $k_{\alpha i}=[1,0.5]^T$, $\mu_{iw}=20$, $k_{iw}=0.5$, $\rho_{io}=2.5$, $\rho_{ij}=1.5$, $\rho_{di}=5$, $k_{\sigma i}=400$, $\Gamma_{si}=40$, $\Gamma_{bi}=1$, $k_{vi}=[5,5]^T$, and $k_{\sigma i}=[40,40]^T$, The initial states are chosen as: $(x_9,y_9,\psi_9)=(8,8,\pi/4)$, $(x_{10},y_{10},\psi_{10})=(14,2,\pi/4)$, $(x_1,y_1,\psi_1)=(-3,8,0)$, $(x_2,y_2,\psi_2)=(2,2,\pi/6)$, $(x_3,y_3,\psi_3)=(8,-5,0)$, $(x_4,y_4,\psi_4)=(14,8,0)$, $(x_5,y_5,\psi_5)=(10,15,0)$, $(x_6,y_6,\psi_6)=(15,-4,\pi/4)$, $(x_7,y_7,\psi_7)=(2,12,0)$, $(x_8,y_8,\psi_8)=(10,-10,0)$, $[x_{1o},y_{1o}]^T=[30,23]^T$, $[x_{2o},y_{2o}]^T=[40,19]^T$, $[x_{d1},y_{d1}]^T=[-9,-3]^T$, $[x_{d2},y_{d2}]^T=[-6,-6]^T$, $[x_{d3},y_{d3}]^T=[-3,-9]^T$, $[x_{d4},y_{d4}]^T=[13,13]^T$, $[x_{d5},y_{d5}]^T=[10,16]^T$, $[x_{d6},y_{d6}]^T=[16,10]^T$, $[x_{d7},y_{d7}]^T=[1,7]^T$, and $[x_{d8},y_{d8}]^T=[10,-2]^T$. Fig. 3 shows the communication topology among the follower USVs and targets.

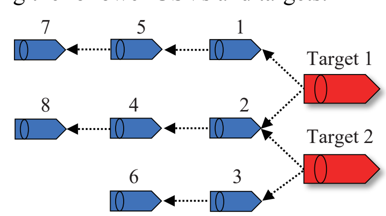

Fig. 3. Communication topology.

Simulation results are given in Figs. 4−6. Fig. 4 shows that the eight follower USVs can track two targets under two stationary obstacles. Fig.5 shows that the estimation performance of the DCESO. Fig. 6 shows the tracking errors.

Conclusions: This letter addresses the problem of multiple targets

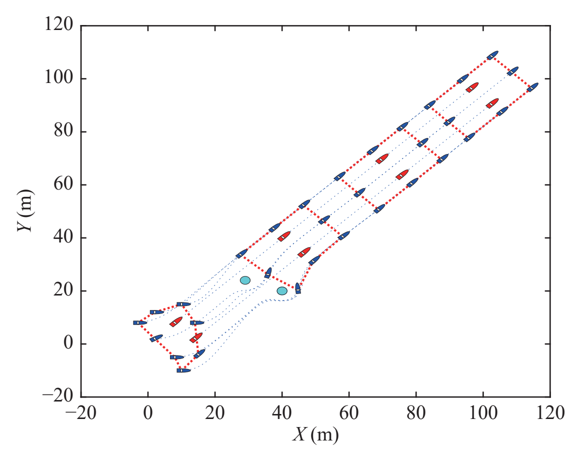

Fig. 4. Safety-critical model-free control performance.

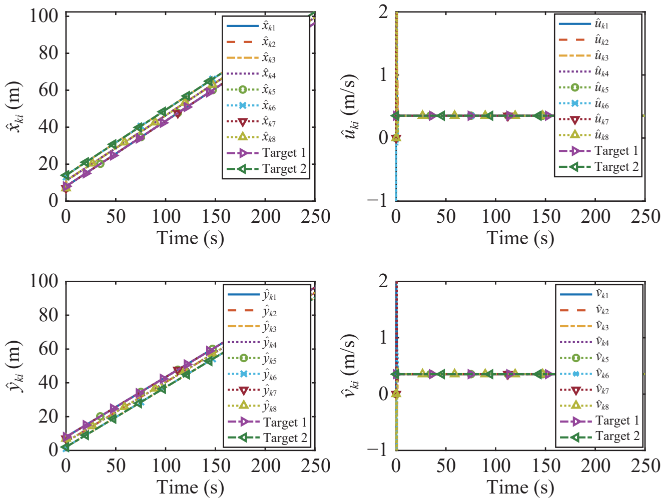

Fig. 5. Estimation performance of the DCESO.

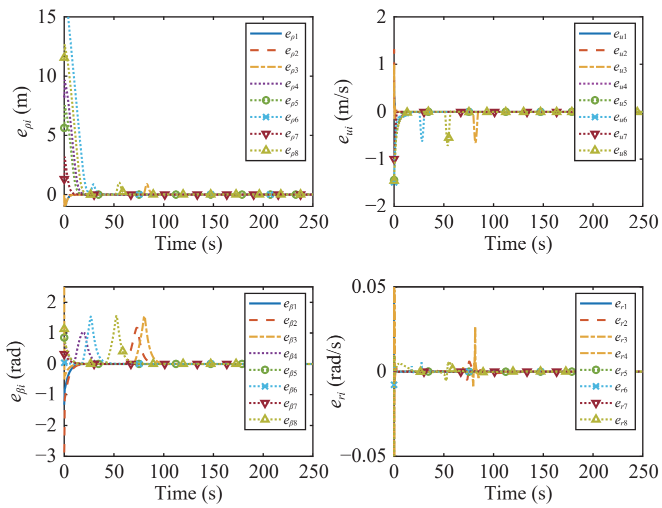

Fig. 6. Tracking errors.

tracking of USVs in the presence of multiple stationary/moving obstacles, in addition to completely unknown kinetics. A DCESO is designed to estimate the convex hull formed by the multi-target. At the kinematic level, a collision-free kinematic guidance law is designed for each follower USV based on a CBF and an ESO. At the kinetic level, a model-free position tracking control law based on an AESO is proposed for each follower USV. Simulations are provided to illustrate the efficacy of the proposed safety-critical model-free control method for USVs.

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