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Robust adaptive enclosing control for multi-robot systems: a circumferential velocity method

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Enclosing control, a key technology in multi-robot cooperative control, has shown significant applications in civil and military scenarios [1,2], such as cooperative escort and military target capture. These scenarios rely on rational robot motion planning to achieve effective target control, but existing technologies struggle in dynamically changing environments. Traditional research focuses on static or simple dynamic targets, but real-world targets have uncertain motions, especially sudden speed changes. For example, monitored animals may suddenly accelerate from slow to fast movement. While some studies [3] have addressed dynamic targets with unknown speeds under pure bearing measurements, control strategies fail to adapt to significant speed mutations, causing formation collapse.

Existing pure bearing-based methods use fixed circumferential speeds, which fail when target speeds mutate. As shown in [4], the formation collapses immediately after a speed change at 50 s due to insufficient tangential speed. Actuator failures, often ignored in current methods [1–5], severely impact formation stability, especially in leader robots due to hardware aging or environmental interference. High-precision control under nonholonomic constraints is another challenge. Achieving high-precision control under nonholonomic constraints is also a major challenge in current multi-robot enclosing control research. Relevant studies such as [1–3] have explored multi-robot enclosing control, but they have obvious deficiencies in handling the collaborative problem between robot nonholonomic kinematic constraints and ensuring control precision.

In practical application scenarios such as wild monitoring and military operations, the uncertainty of target speeds, potential risks of hardware failures, and strict requirements for control precision urgently demand a new multi-robot enclosing control method that can adapt to target speed changes, have strong fault-tolerant capabilities, and achieve high-precision control effects to meet mission requirements in complex dynamic environments.

To address the aforementioned issues, an adaptive circumferential velocity-based fault-tolerant enclosing control issue is studied in this article based on pure bearing measurements. Compared with existing results, the innovations and main contributions of this study are as follows. (1) This study proposes an adaptive enclosing control scheme for multi-robot systems with pure bearing measurements. Via adaptive law design for robots' circumferential velocity, it tackles sudden velocity changes of unknown targets. Unlike [1–5], where bearing-only enclosing control fails during target velocity shifts, this method ensures the robot-target relative circular velocity exceeds a lower bound, maintaining formation. (2) The designed intermediate variables and controllers can compensate for fault signals that occur in incomplete robots during the enclosing process. Furthermore, precision limits are set while ensuring the robot's safety, and innovatively, fault and non-completeness constraint strategies are incorporated into the enclosing control framework based on pure bearing measurements. Compared to [3–5], smooth functions and adaptive laws are used to address potential actuator faults and ensure that the incomplete robot converges to the desired formation according to the predefined control constraints.

Method. The kinematical model of the nonholonomic robot i can be established as

$$\begin{cases} \dot{x}_i(t) = \cos\varphi_i(t)v_i(t), \\ \dot{y}_i(t) = \sin\varphi_i(t)v_i(t), \\ \dot{\varphi}_i(t) = \omega_i(t), \end{cases} \tag{1}$$

where x_i and y_i represent the position information of robot i, φ_i is the heading angle of robot i with respect to the x-axis, v_i and ω_i are the linear velocity and angular velocity of robot i, respectively.

Assumption 1 ([4]). At the initial moment, the subtended angle and separation angle must meet safety conditions, such as the robot's sensors can detect the target and adjacent robots, and the leader robot's separation angle from robot 1 satisfies $\upsilon_n \leqslant 2\pi - \sum_{i<n} \upsilon_i$, which means $\mu_{\min,i} < \mu_i(0) < \mu_{\max,i}$ and $\upsilon_{\min,i} < \upsilon_i(0) < \upsilon_{\max,i}$, $i = 1, 2, ..., n$.

Assumption 2 ([3]). The velocity of the target's movement is constrained within certain bounds; that is, there is a constant v_{m0} such that $||v_0|| \leqslant v_{m0}$.

Assumption 3. For piecewise continuous and bounded unknown time-varying signal u_{ih}, there exists a constant $\bar{u}_{ih}$ such that $u_{ih} \leqslant \bar{u}_{ih}$ holds.

Control objective. Based on Assumptions 1–3, this study is to design a fault-tolerant controller for adaptive circumferential

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velocity, enabling multiple robots to form and maintain an enclosing formation around the target using only bearing information. Additionally, all closed-loop signals are bounded, and the angular error signal stays within the specified constraints.

To break through the above issues, this study constructs a robust control framework integrating adaptive circumferential speed control, fault compensation, and constraint integration. Its core innovation lies in designing an adaptive law for the robot's circumferential speed based on geometric principles, ensuring that the relative speed between the robot and the target in the tangential direction always remains above the preset lower limit through real-time adjustment, as shown in Figure 1.

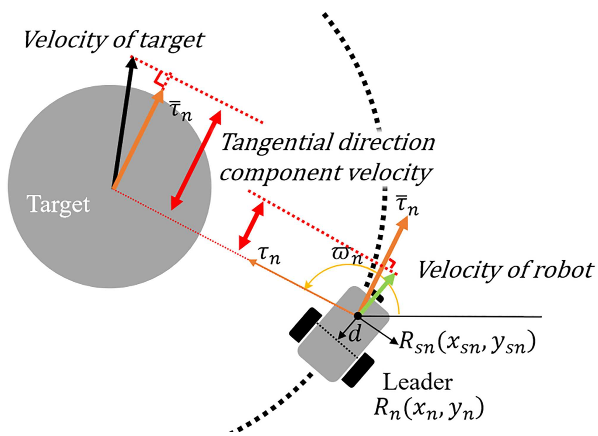

Figure 1 (Color online) Relative velocity of the target and the robot in the tangent direction.

Specifically, for target speed estimation errors and circumferential speed errors, dynamic update laws are designed to enable robots to adjust speed parameters in real-time according to target motion states; see Appendix B.2 for details. An adaptive law is constructed to estimate the upper bound of the target speed, and the robot's circumferential speed is adjusted based on this to maintain relative motion balance when the target speed mutates, as follows:

$$\dot{\hat{v}}_{mi0} = -k_{2i}\hat{v}_{mi0} + \frac{B_{1i}^2}{\sqrt{B_{1i}^2 + \varepsilon_i}}, \quad i = n, \tag{2}$$

$$\dot{\hat{v}}_{mi0} = -k_{2i}\hat{v}_{mi0} + \frac{B_{1i}^2}{\sqrt{B_{1i}^2 + \varepsilon_i}} + \frac{B_{2i}^2}{\sqrt{B_{2i}^2 + \varepsilon_i}}, \quad i < n, \tag{3}$$

$$\dot{w} = -k_w(w - \hat{v}_{mn0} - \underline{w}_d). \tag{4}$$

Lemma 1 ([4]). For any variable x, positive uniform continuous and bounded function $\eta(t)$, if the equations $0 \leqslant |x| - \frac{x^2}{\sqrt{x^2+\eta^2(t)}} < \eta(t)$ and $|x| - \frac{x^2}{|x|+\eta(t)} < \eta(t)$ hold, then $\eta(t)$ satisfies $\lim_{t\to\infty} \int_{t_0}^{t} \eta(\omega)d\omega \leqslant \bar{\eta} < \infty$, where $\bar{\eta}$ is any given positive constant.

The proof of Lemma 1 can be found in Appendix B.1.

Theorem 1. Under Assumptions 1–3, for the nonholonomic actuated robotic system (1) with actuator faults, the adaptive laws (2)–(4), (B4), (B8) and the control laws (B9), (B10) are constructed, and by selecting suitable parameters k_2 and k_w such that $k_2 > k_w$, the designed robust adaptive surround formation control scheme can ensure that (1) all closed-loop signals are bounded, (2) the angle error of each robot can be constrained to the desired neighborhood, (3) the formation can converge to the desired enclosing formation, regardless of the target's varying velocity at different times.

The proof of Theorem 1 can be found in Appendix B.2.

Experiment. The experiment verifies the effectiveness of the method by comparing scenarios of target uniform speed, variable speed, and actuator failure; see Appendix C for details. When the target speed mutates at 50 s, the subtended angle error and separation angle error of the proposed method quickly converge and remain within the boundary, while the method in [3] shows separation angle divergence and formation collapse after the speed mutation. When the actuator failure occurs in robot 2 at 70 s, the proposed method uses compensation signals to make the angle error stabilize after fluctuations, verifying the robustness of the fault-tolerant mechanism. Experimental results show that the adaptive circumferential speed mechanism can effectively cope with a 10-fold mutation in target speed, and the fault compensation signal can maintain error constraints when the actuator fails, proving the superiority of the method in dynamic environments.

Conclusion. The core innovations of this study are reflected in three aspects: first, an adaptive enclosing control based on pure bearing measurement is proposed, which solves the problem of target speed mutation through a circumferential speed adaptive law; second, intermediate variables and controllers are designed to compensate for actuator failures, filling the gap in fault-tolerant control in pure bearing measurement enclosing; third, precision and nonholonomic constraints are integrated, enabling robots to meet preset indexes and converge to the desired formation. Future research can be expanded to multi-target control, multi-robot obstacle avoidance, algorithm optimization, and sensor noise robustness.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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