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ORIGINAL RESEARCH

Target localization and encirclement control for multi-UAVs with limited information

Weizhen Wang | Xin Chen | Jiangbo Jia | Zaifei Fu

College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China

Correspondence
Weizhen Wang, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China.
Email: wang_weizhen18@163.com

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Abstract

The problem of localization and encirclement control of a moving target by multi unmanned aerial vehicles (UAVs) is considered in this paper. The main objective is to guide the UAVs to form evenly spaced formations along the circumference, with the centre of the circumference tracking the movement of the target. Firstly, each UAV is assumed only to obtain the bearing angle information of the target, for which an estimator is developed to localize the target by bearing measurements. Thereafter, a distributed encirclement control algorithm based on cooperative moving path following (CMPF) is designed to drive the multi-UAVs to circumnavigate around a moving target at a desired distance, thus developing to pursue cooperatively. Finally, the simulation results demonstrate the effectiveness of the proposed method.

1 | INTRODUCTION

Up to now, unmanned aerial vehicles (UAVs) have been widely used in military and civilian applications, such as area surveillance [1–3], target tracking [4–6], environmental protection and navigation [7–11]. Among the many proposed UAV application scenarios, the target enclosing problem has become a popular research topic in recent years due to its multiple application prospects, including target pursuit and surveillance tasks. However, in most existing results, control algorithms for multi-UAVs enclosing a target are usually developed under the assumption that the target location is known to the UAVs. When the target position and velocity are unknown, an estimator is generally presented for the UAVs to estimate the target state. Then the obtained estimation information is used to design a controller to achieve a circular formation. In this case, both target localization and enclosing control should be considered simultaneously.

The target encirclement problem, also known as the circumnavigation or cyclic pursuit problem, has been studied for monitoring or protecting ground motion targets in ref. [12–14] and has attracted extensive research attention. In ref. [15], the moving path following (MPF) problem is first studied; however, its UAV control law based on Lyapunov derivation is more conservative. Moreover, in practice, there is a preference for using multiple small and low-cost UAVs to complete complex tasks for efficiency in mission accomplishment and greater robustness of UAV formations in the event of an accident. In this scenario, a new motion control problem is defined, namely the cooperative motion path following (CMPF) problem, which requires the formation of UAVs to converge to a desired geometric motion path while satisfying pre-specified speed and space constraints [16]. In ref. [17], the CMPF problem of multi-fixed-wing UAVs under stringent velocity constraints and collision-free maneuver requirements is addressed, and nonsingular control law is developed to avoid the singularity problem in ref. [15]. The authors in ref. [18] recently proposed a distributed estimation and control strategy to solve the distance-based target localization and pursuit problem utilizing single or multiple trackers, where the MPF is used to plan the trackers' trajectories.

However, these work, is carried out under the condition that the tracker can obtain the target position information. In many practical applications, it is difficult for UAVs to measure the target's complete relative position information (distance and bearing angle). For example, in some cases, UAVs that are not equipped with lidar cannot make distance measurements. And the bearing measurement requires only common types of sensors, such as monocular camera systems, which make it easier to obtain for UAVs equipped with only cameras. Through the above analysis, it can be concluded that the development of circumnavigation algorithms with less dependence on sensor measurement information is a promising option. Thus, the bearing-based control method has widely concerned by scholars, and the relevant results have been reported [19–22]. In ref. [23], a control protocol based on the local bearing-only information is developed to estimate the target distance and speed by the circumnavigating agent. An estimator employing bearing information is introduced in ref. [24] to localize a moving target, and a corresponding distributed controller is developed to make the agent move along the common circle with the specified radius centered on the target. Different from the research of references [24] in two-dimensional plane, the localization and circumnavigation problem of an unknown stationary target in three-dimensional space is investigated in ref. [25], in which a system design framework combining estimator, controller and coordinator is proposed. Moreover, unlike the use of estimators, a solution to the target tracking problem of the vehicles in a circular formation is presented in ref. [26] using a robust control concept, which has better anti-disturbance characteristics.

Based on the above discussions, we can conclude that the target localization and encirclement control issue of multi-UAVs with limited information is a challenging task with two essential difficulties identified as follows:

(1) how to obtain the relative position of the moving target with bearing-only measurements.
(2) how to design bearing based distributed encirclement control algorithm combined with CMPF under which the UAVs can converge to any desired spacing circular formation or its neighborhood around a moving target.

Thus, this study addresses multi-UAVs' localization and encircling a moving target using bearing-only measurements. Our goal is to develop a localization algorithm and control law that uses only the bearing angle of the target to estimate the relative position of the target. At the same time, drive the UAVs to circumnavigate around a moving target at the desired distance. In this study, we first consider that when the target velocity is unknown, an estimator is proposed for each UAV to obtain the relative position of the target based on the bearing measurements of itself to the target. Then, the CMPF is used to drive the UAVs to converge to the exact desired spacing circular formation around the moving target. Finally, simulation results show the effectiveness of the proposed method. The main advantages of the developed strategy are embodied as follows.

(1) An estimator with bearing-only measurements is proposed and the relative positions of the pursuing UAVs concerning the target are expressed in the local frame of each UAV.
(2) A cooperative moving path following control law is designed to make the UAVs and its neighbors along the common circle with a specified radius centered on the target while achieving a uniform spacing pattern.
(3) The proposed strategy requires only limited information exchange between UAVs, thus improving the applicability in practical applications.

This paper is organized as follows. Section 2 formulates the CMPF problem. The main results are presented in Section 3. Simulation results are given in Section 4. Section 5 provides conclusions and future of this work.

Notation. The notations used in this paper are fairly standard. P^T represents its transpose and I represents the identity matrix with compatible dimension. $\mathbf{0}$ is a matrix whose entries are all zero. $\mathbf{1}_N$ is a column vector with N rows and whose entries are all one. Given a symmetric matrix A, the symbols $\lambda_{\min}(A)$ denote the smallest eigenvalues of A. $\|\cdot\|$ represents the Euclidnorm of a vector. Diagonal matrix is defined as $diag(x) = diag(x_1, x_2, x_3)$ for $x = [x_1, x_2, x_3]^T$.

2 | PROBLEM FORMULATION

2.1 | Graph theory

Consider a directed graph $\mathcal{G} = \mathcal{G}(\mathcal{V}, \mathcal{E}, \mathcal{A})$ which is used to describe the information communication topology between the UAVs, where $\mathcal{V} = \{1, 2, \dots, N\}$ is a set with finite nodes, $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is a set of directed edges, and $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N\times N}$ denotes an adjacency matrix. $\mathcal{N}_i = \{j \in \mathcal{V} | (i, j) \in \mathcal{E}\}$ denotes the set of the neighbouring nodes for node i. The adjacency matrix $\mathcal{A} = [a_{ij}]$, with $a_{ij} = 1$ if $j \in \mathcal{N}_i$, otherwise, $a_{ij} = 0$ Let $L = \mathcal{D} - \mathcal{A} \in \mathbb{R}^{N\times N}$ be the Laplacian of the network connection graph and define $\mathcal{D} = diag(|\mathcal{N}_1|, |\mathcal{N}_2|, \dots, |\mathcal{N}_N|)$.

2.2 | Model of the UAVs

In this paper, we suppose that all UAVs fly at a fixed attitude during the tracking process. Therefore, the motion of the UAV can be simplified as

$$\begin{cases} \dot{p}_i = R(\theta_i)[v_i,\ 0]^{\mathrm{T}} \\ \dot{\theta}_i = \omega_i \end{cases}, \tag{1}$$

where p_i is the position of UAV i, θ_i is the heading angle of the UAV, v_i and ω_i are the airspeed and heading rate, respectively. $R(\theta_i)$ denotes the rotation matrix from body to inertial reference frame, defined by $R(\theta_i) = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix}$. $u_i = [v_i,\ \omega_i]^{\mathrm{T}}$ is the control input of UAV i.

As illustrated in Figure 1, denote $p_{i0} = p_0 - p_i$ is the relative position of the target in UAV i's local frame. The relative position of the target p_{i0} is unknown to UAV i. We assume that each agent can measure the bearing angle to the target θ_i. The distance between the UAV i and the target is $\rho_i = \|p_{i0}\|$. Define φ_i as the unit vector on the line passing through the UAV i and the target, that is

$$\varphi_i = \frac{p_0 - p_i}{\|p_0 - p_i\|} = \frac{p_{i0}}{\rho_i}. \tag{2}$$

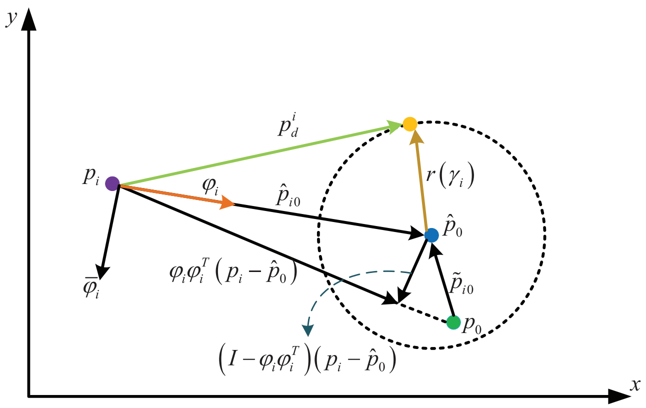

FIGURE 1 Illustration of the proposed methodology.

Besides, $\bar{\varphi}_i$ be the unit vector obtained by $\pi/2$ clockwise rotation of φ_i.

As the target position is unknown to the UAVs, UAV i needs to estimate the relative position of the target. Define $\hat{p}_{i0}$ as the estimation of target relative position by UAV i and $\hat{\rho}_i = \|\hat{p}_{i0}\|$ represents its estimated distance to the target.

2.3 | Moving path following problem

The seminal study of MPF for UAVs can be found in [15], in which a generic path tracking controller for UAVs at the kinematic level is proposed. In this case, the designed control law drives the real vehicle to follow the movement path of the virtual target to achieve the control purpose. Let $\mathcal{P}: \gamma_i \rightarrow r(\gamma_i)$ be a path denoted in an inertial frame, one has that

$$r(\gamma_i) = [r_x^i \cos(\gamma_i + \gamma_0^i), r_y^i \sin(\gamma_i + \gamma_0^i)]^{\mathrm{T}}, \tag{3}$$

where γ_i is a path parameterizing variable, and r_x^i, r_y^i and γ_0^i are constant parameters.

Set the virtual reference point that UAV i needs to follow as p_d^i, which is defined as

$$p_d^i = r(\gamma_i) + \hat{p}_{i0} \tag{4}$$

In order to make the virtual point p_d^i move along the desired path, the dynamics of the path variable $\dot{\gamma}_i$ need to be controlled explicitly. Therefore, the dynamics of γ_i is set as

$$\dot{\gamma}_i = \omega_d^i + g_e^i, \tag{5}$$

where g_e^i is a correction signal to be defined in next section, ω_d^i is the desired nominal speed of the virtual point.

2.4 | Main objectives

The main work of this paper is to accomplish the complete the following three design objectives.

(1) Design an estimator to estimate the relative position of the target, and the estimation error of the relative position converge to neighborhoods of zero, we have

$$\lim_{t\rightarrow\infty} \|\tilde{p}_{i0}\| \leq U_p, \quad \forall i \in \mathcal{V}. \tag{6}$$

(2) A controller is proposed to make the tracker converge and follow the desired trajectory given by (4), one has

$$\lim_{t\rightarrow\infty} |p_i - p_d^i| = 0, \quad \forall i \in \mathcal{V}. \tag{7}$$

(3) Each UAV in the team need operate at a desired angular speed $\bar{\omega}$ around the moving target, that is, the path parameters of the UAVs are consensus to reach the desired formation.

$$\lim_{t\rightarrow\infty} |\gamma_i - \gamma_j| = 0, \quad \forall i, \quad j \in \mathcal{V}, \tag{8}$$

$$\lim_{t\rightarrow\infty} \dot{\gamma}_i = \bar{\omega}. \tag{9}$$

To deal with the problem of cooperative target localization and tracking under the coordination requirements in (8), a distributed control system for each UAV is proposed. The primary ideas of this study are briefly described as follows

(1) *Relative position estimation:* In this part, the main objective is to deal with the target location task (6) when the UAVs only obtain the bearing angle information to the target. To do this, inspired by the work in [24], we develop a localization algorithm for each UAV to estimate the relative position of the target.
(2) *Encirclement control:* The goal of this controller is to make the multi-UAVs converge to the specified trajectory given by (4), that is, complete the tracking task given by (7). Using the concept of MPF proposed in [15], a path defined as (3) and the UAVs can encircle the target with a desired angular speed $\bar{\omega}$.
(3) *Cooperative control:* In this module, the main purpose is to complete the coordination task (8). The solution is to use the neighbourhood information γ_j and local information γ_i to calculate the correction speed ϑ_i to obtain a distributed consensus control law. The nominal speed $\bar{\omega}$ is to coordinate the path parameters and finally reached the consensus.

Remark 1. If the paths $r(\gamma_i)$ is parameterized appropriately designed such that $\gamma_i - \gamma_j = 2\pi/N$ for $N \geq 3$, where $i \neq j$ are any two adjacent UAVs, then each member in the team will attempt to spread itself evenly in a circular formation around the target.

3 | LOCALIZING AND ENCLOSING A TARGET

Considering that the UAV can only obtain the bearing information of the target, it cannot directly use the position information of the target to design the controller. In this case, the problems of target localization and encirclement control can be divided into estimation and control problems. First, an estimator is developed for each UAV to estimate the relative position of the target. Then a distributed encirclement control algorithm based on CMPF is developed to make the multi-UAVs converge to a common circle.

3.1 | Target relative position estimator design

This study consider the case that the target is moving with a bounded but unknown velocity. Then, make the following assumptions about the motion of the target.

Assumption 1. The target trajectory p_0 is differentiable and there exists a positive constant ζ such that

$$\alpha - \|\dot{p}_0\| \geq \zeta > 0, \quad \forall t > 0, \tag{10}$$

where $\alpha > 0$ represents the tangential speed of the moving target.

Remark 2. As pointed out in ref. [24] and [25], in order for the UAV to circumnavigate the target, the UAV and the target speed should satisfy some conditions. It is assumed that the velocity of UAV along unit vector $\bar{\varphi}_i$ is greater than the target velocity, which is called the tangential velocity of UAV in this paper. Under this assumption, it is guaranteed that the UAV speed is always greater than the target speed, and thus the UAV will be able to circumnavigate the target.

Employing the bearing of the target, following [24], an estimator of $\hat{p}_{i0}$ is introduced to estimate the target relative position of p_{i0},

$$\dot{\hat{p}}_{i0} = k_i\left(I - \varphi_i\varphi_i^{\mathrm{T}}\right)(p_i - \hat{p}_0), \tag{11}$$

where I is an identity matrix of appropriate dimensions, k_i is a positive constant and $\varphi_i\varphi_i^{\mathrm{T}}$ is a projection matrix onto the vector φ_i. If the estimated target relative position $\hat{p}_{i0}$ approaches p_{i0}, then it is reasonable to use $\hat{p}_{i0}$ design controller.

Lemma 1 [24]. *For the following dynamic system $\dot{x} = A(t)x + f(t)$, where $x(t_0) \neq 0$, $0 \leq t_0 \leq t \leq \infty$. Let the coefficient matrix $A(t)$ is continuous for all $t \in [0, \infty]$, and positive constants r, b exist such that for every solution of the homogeneous differential equation $\dot{x} = A(t)x$ has $\|x\| \leq b\|x(t_0)\|e^{-r(t-t_0)}$. Then for each $f(t)$ bounded and continuous on $[0, \infty]$, every solution of the system $\dot{x} = Ax + f(t)$ is bound for $t \in [0, \infty]$. If $\|f(t)\| \leq K_f < \infty$, then the solution of the perturbed system satisfies*

$$\|x\| \leq b\|x(t_0)\|e^{-r(t-t_0)} + \frac{K_f}{r}\left(1 - e^{-r(t-t_0)}\right). \tag{12}$$

Theorem 1. *The estimation error of target relative position by UAV i is defined as $\tilde{p}_{i0} = \hat{p}_{i0} - p_{i0}$, thus the estimation method (11) designed in this paper can make the estimation error $\tilde{p}_{i0}$ converge exponentially fast to a circular area of radius $\frac{\alpha-\zeta}{r}$ centered at origin as $t \to \infty$.*

Proof. Equation (11) can be rewritten as

$$\dot{\hat{p}}_{i0} = k_i\bar{\varphi}_i\bar{\varphi}_i^{\mathrm{T}}(p_i - \hat{p}_0). \tag{13}$$

Considering φ_i defined in (2), we have

$$k_i\bar{\varphi}_i\bar{\varphi}_i^{\mathrm{T}}(p_i - p_0) = 0. \tag{14}$$

With this property, the estimation error dynamics can be written as

$$\begin{aligned}\dot{\tilde{p}}_{i0} &= \dot{\hat{p}}_{i0} - \dot{p}_{i0}\\ &= k_i\left(I - \varphi_i\varphi_i^{\mathrm{T}}\right)(p_i - \hat{p}_0) - \dot{p}_0\\ &= k_i\bar{\varphi}_i\bar{\varphi}_i^{\mathrm{T}}\tilde{p}_{i0} - \dot{p}_0.\end{aligned} \tag{15}$$

If $\dot{p}_0 = 0$, choose the Lyapunov function as

$$V_1 = \frac{1}{2}\tilde{p}_{i0}^{\mathrm{T}}\tilde{p}_{i0}. \tag{16}$$

Then

$$\begin{aligned}\dot{V}_1 &= -k_i\tilde{p}_{i0}^{\mathrm{T}}\bar{\varphi}_i\bar{\varphi}_i^{\mathrm{T}}\tilde{p}_{i0}\\ &= -k_i\|\bar{\varphi}_i^{\mathrm{T}}\tilde{p}_{i0}\|^2.\end{aligned} \tag{17}$$

It can be see that the $\dot{V}_1$ is negative semi-definite and $\|\tilde{p}_{i0}\|$ is a monotone decreasing function, that is, $\|\tilde{p}_{i0}(t)\| \leq \|\tilde{p}_{i0}(0)\|$. If $\dot{p}_0 \neq 0$, then by the assumption 1 and Lemma 1, $\tilde{p}_{i0}$ will converge exponentially fast to the circular area centered at origin with radius

$$\frac{\max_t \|\dot{p}_{i0}\|}{r} = \frac{\alpha - \zeta}{r}, \tag{18}$$

as $t \to \infty$. The proof is complete. □

3.2 | MPF controller design

In this subsection, the man goal is to develop a distributed control law to make the multi-UAVs along the desired trajectory defined in (3). After getting the relative position of the target, the error between the UAV i and the desired trajectory is defined as follows:

$$\begin{aligned}\hat{e}_i &= R^{\mathrm{T}}(\theta_i)(p_i - p_d^i) - \delta\\ &= R^{\mathrm{T}}(\theta_i)(p_i - r(\gamma_i) - \hat{p}_{i0}) - \delta,\end{aligned} \tag{19}$$

where δ is an arbitrarily small nonzero vector. Taking its time derivative and combination (1) and (11), one has that

$$\begin{aligned}\dot{\hat{e}}_i &= -S(\omega_i)\hat{e}_i - S(\omega_i)\delta + R^{\mathrm{T}}(\theta_i)(\dot{p}_i - r'(\gamma_i)\dot{\gamma}_i - \dot{\hat{p}}_{i0})\\ &= -S(\omega_i)\hat{e}_i + \Delta u - R^{\mathrm{T}}(\theta_i)(r'(\gamma_i)\dot{\gamma}_i + \dot{\hat{p}}_{i0}),\end{aligned} \tag{20}$$

where $\Delta = \begin{bmatrix} 1 & \delta_2 \\ 0 & -\delta_1 \end{bmatrix}$, $S(\omega_i) = \begin{bmatrix} 0 & -\omega_i \\ \omega_i & 0 \end{bmatrix}$.

Theorem 2. *Consider the UAV model with dynamics described by (1) and the CMPF error kinematics model (20). Assume that the target position can be obtained by estimator (11). Design the control law*

$$u_i = \Delta^{-1}\left(R^{\mathrm{T}}(\theta_i)(r'(\gamma_i)\dot{\gamma}_i + \dot{\hat{p}}_{i0}) - k_e\hat{e}_i\right), \tag{21}$$

ensures that the origin $\hat{e}_i = 0$ of the CMPF error are globally asymptotically stable.

Proof. Similar to (19), let

$$e_i = R^{\mathrm{T}}(\theta_i)(p_i - r(\gamma_i) - p_{i0}) - \delta. \tag{22}$$

From (19) and (22), one has

$$\hat{e}_i = e_i - R^{\mathrm{T}}\tilde{p}_{i0}. \tag{23}$$

Then, taking (22) time derivative and we can obtained that

$$\dot{e}_i = -S(\omega_i)e_i + \Delta u - R^{\mathrm{T}}(\theta_i)(r'(\gamma_i)\dot{\gamma}_i + v). \tag{24}$$

Combine (21) and denote $e_\gamma^i = \dot{\gamma}_i - \omega_d^i$, we have

$$\dot{e}_i = -S(\omega_i)e_i + R^{\mathrm{T}}(\theta_i)(\tilde{v}_i - r'(\gamma_i)e_\gamma^i) - k_e\hat{e}_i, \tag{25}$$

where $\tilde{v}_i = \dot{\hat{p}}_{i0} - v_i$ is the estimation error of the target's velocity.

Consider the Lyapunov function as follow

$$V_2(e_i) = \frac{1}{2}\|e_i\|^2. \tag{26}$$

Differentiating $V_2(e_i)$ along the solutions of the closed-loop dynamics (10) yields

$$\begin{aligned}\dot{V}_2(e_i) &= e_i^{\mathrm{T}}\dot{e}_i\\ &= -e_i^{\mathrm{T}}k_e e_i + e_i^{\mathrm{T}}R^{\mathrm{T}}(\theta_i)\tilde{v} + e_i^{\mathrm{T}}k_e R^{\mathrm{T}}(\theta_i)\tilde{p}_{i0}\\ &\le -\lambda_{\min}(K)\|e_i\|^2 + (1 + \|K\|)\|e_i\|\|\tilde{x}_i\|\\ &\le -(1-\theta)\lambda_{\min}(K)\|e_i\|^2 \quad \forall\|e_i\| \ge \Theta,\end{aligned} \tag{27}$$

where $\Theta = \frac{(1+\|K\|)\|\tilde{x}_i\|}{\theta}$, $\theta \in (0,\ 1)$, $\tilde{x}_i = [\tilde{v}_i^{\mathrm{T}}, \tilde{p}_{i0}^{\mathrm{T}}]^{\mathrm{T}}$. According to [18], it can be conclude that the tracking error system is globally asymptotically stable. The proof is complete. □

3.3 | Cooperative target pursuit

Next, the controller is designed for each UAV to complete the cooperative control problem of target tracking described in the main objectives (3). Therefore, a distributed control law of correction speed ϑ_i in consensus protocol form is presented as

$$\vartheta_i = -k_c^i \sum_{j\in\mathcal{N}_i}(\gamma_i - \gamma_j), \tag{28}$$

where $k_c^i > 0$ is a constant. Combined with the correction speed ϑ_i, the total expected speed to be tracked by γ_i is expressed as follows

$$\omega_d^i = \bar{\omega} + \vartheta_i. \tag{29}$$

Further, considering that when the actual trajectory of UAV is quite different from the virtual trajectory p_d^i, the correction term g_e^i is introduced to delay or suspend the change of path parameter γ_i. Employing the gradient of the path error (19) squared concerning the path variable, one has

$$\eta_e^i = \frac{\partial\left(\frac{1}{2}\hat{e}_i^{\mathrm{T}}\hat{e}_i\right)}{\partial\gamma} = -\hat{e}_i^{\mathrm{T}}R^{\mathrm{T}}(\theta_i)\frac{\partial p_d^i}{\partial\gamma_i}. \tag{30}$$

Combined with Equation (30), we define the correction term as $g_e^i = -k_\eta^i\,sat(\eta_e^i)$ with $k_\eta^i > 0$.

Considering (29) in (5) and stacking the dynamic equations, we have

$$\dot{\boldsymbol{\gamma}} = \bar{\omega}\mathbf{1}_N - K_c L\boldsymbol{\gamma} + \mathbf{g_e}, \tag{31}$$

where $\boldsymbol{\gamma} = [\gamma_1,\ \gamma_2, \dots, \gamma_N]^{\mathrm{T}}$, $\mathbf{g_e} = [g_e^1,\ g_e^2, \dots, g_e^N]^{\mathrm{T}}$, $\mathbf{1}_N = [1,\ 1, \dots, 1]^{\mathrm{T}}$, $K_c = diag(k_c^1,\ k_c^2, \dots, k_c^N)$.

Theorem 3. *Suppose the communication directed graph between UAVs is strongly connected. The cooperative control law designed in (28) guarantees that $|\gamma_i - \gamma_j|, \forall i, j \in \mathcal{I}$ is input-to state stable (ISS) with respect to the error correction terms g_e^i.*

Proof. Define the disagreement vector as follows

$$\boldsymbol{\sigma} = \boldsymbol{\gamma} - \frac{1}{N}\mathbf{1}_N\mathbf{1}_N^{\mathrm{T}}\boldsymbol{\gamma}. \tag{32}$$

Note that the consensus condition $\gamma_1 = \gamma_2 = \dots = \gamma_N$ is achieved if and only if $\boldsymbol{\sigma} = \mathbf{0}$, moreover, $L\boldsymbol{\gamma} = L\boldsymbol{\sigma}$ and $\mathbf{1}_N^{\mathrm{T}}\boldsymbol{\sigma} = 0$.

Choosing the Lyapunov function as follow:

$$V_3(\boldsymbol{\sigma}) = \frac{1}{2}\boldsymbol{\sigma}^{\mathrm{T}}L\boldsymbol{\sigma}. \tag{33}$$

Thus, the time derivative of (33) is

$$\dot{V}_3(\boldsymbol{\sigma}) = -z^{\mathrm{T}}K_c z + z^{\mathrm{T}}\mathbf{g_e}, \tag{34}$$

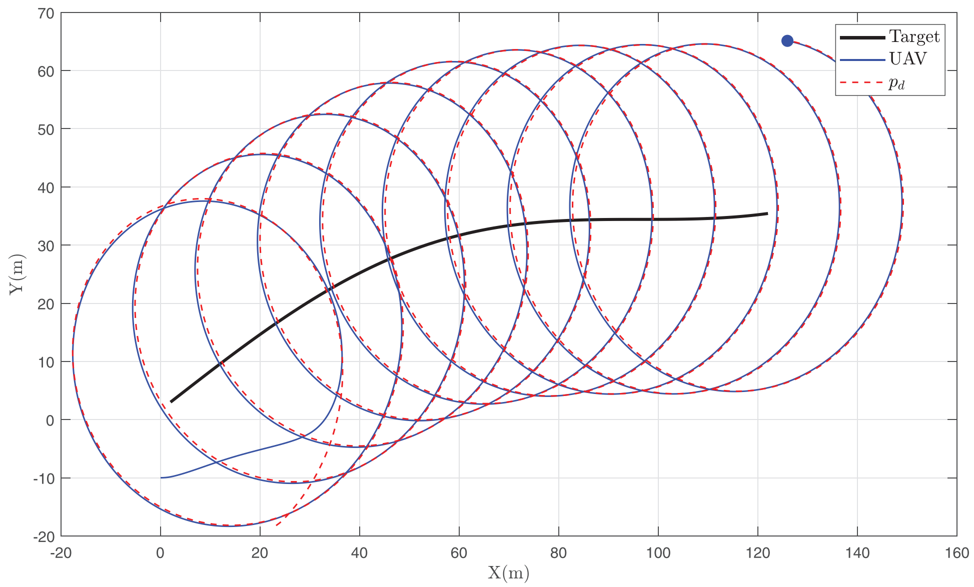

FIGURE 2 Trajectories of the target and single UAVs

where $z = L\boldsymbol{\sigma}$. Employing the Cauchy-Schwartz inequality, one has

$$\dot{V}_3(\boldsymbol{\sigma}) \leq -\lambda_{\min}(K_c)\|z\|^2 + \|z\|\|\mathbf{g_e}\|$$

$$\leq -(\lambda_{\min}(K_c) - \theta)\|z\|^2, \quad \forall \|z\| \geq \frac{\|\mathbf{g_e}\|}{\theta\lambda_{\min}(K_c)}, \tag{35}$$

where $\theta \in (0,\ 1)$. It can be conclude that the disagreement vector z is ISS with respect to the input $\mathbf{g_e}$. The proof is complete. □

4 | SIMULATIONS

In this section, the simulation results of three UAVs for different scenarios are proposed to characterize the effectiveness of the presented strategy. The desired path for the UAV is a circle centered at the target with the radius of ρ_i, which is parameterized by $r(\gamma_i) = [r_x^i \cos(\gamma_i + \gamma_0^i), r_y^i \sin(\gamma_i + \gamma_0^i)]^{\mathrm{T}}$. Next, we verify the effectiveness of the proposed strategy in cases of single UAV and three UAVs tracking moving targets, respectively.

First, in the scenarios of single UAV, the target's trajectory is assumed to be $p_0 = [2 + 0.3t,\ 3 + 10\sin(0.01t) + 0.1t]^{\mathrm{T}}$. The simulation parameters are chosen as $r_x = r_y = 30$, $\rho = 30$ m and $\bar{\omega} = 0.15$ rad/s. The trajectories of single UAV is shown in Figure 2, which indicates that the UAV converges to and stay in the vicinity of the moving target and enclosing the latter. Figure 3a,b shows that the estimation error of relative position and the encirclement errors, respectively. Figure 3c demonstrates the distance between the moving target and each UAV, that is, the desired envelope radius ρ. Figure 4a and 4b illustrate the evolution of the path parameters, from which it is not difficult to observe that the path parameter reaches the expected angular rate.

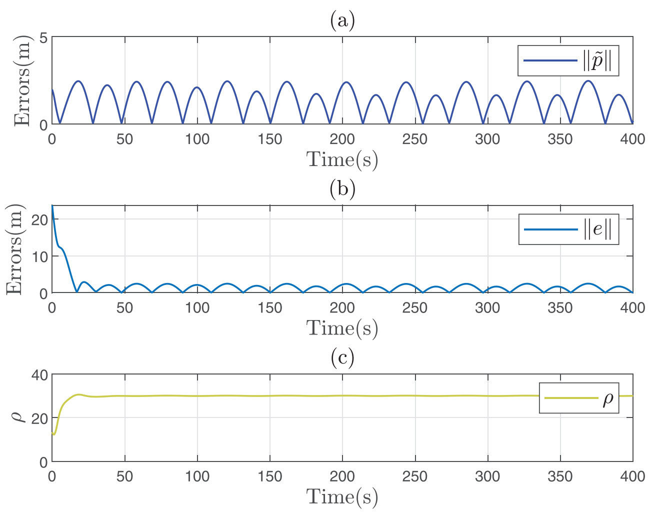

FIGURE 3 Simulation results. (a) Evolution of the estimation error of the relative target position by the UAVs. (b) Time evolution of the encirclement errors. (c) Distance between the UAVs and the moving target

After that, the scenarios of three UAVs tracks the move target is simulated. The trajectory of the moving target expressed is denoted by $p_0 = [2 + 0.2t,\ 2 + 3\sin(0.08t + 2)]^{\mathrm{T}}$. Furthermore, the target moving with a bounded velocity 2m/s. Set the parameters r_x^i and r_y^i to 30, $\gamma_0^1 = 0$, $\gamma_0^2 = 2\pi/3$, $\gamma_0^3 = -2\pi/3$. The consensus gains are $k_c^i = 0.2$ for $i = 1,\ 2,\ 3$. The controller gain matrices k_e and the construction of the CMPF errors ϵ are choose as $diag(0.2, 0.2)$ and $[-0.5, 0]^{\mathrm{T}}$, respectively. The reference for the path variable velocity is $\bar{\omega} = 0.15$ rad/s. Besides, the target relative position estimator gain k_i is set as 0.85.

The trajectories of the target and three UAVs is exhibited in Figure 5. Figure 6a illustrates that the estimation error of the relative target position $\|\tilde{p}_{i0}\|$ by each UAV.

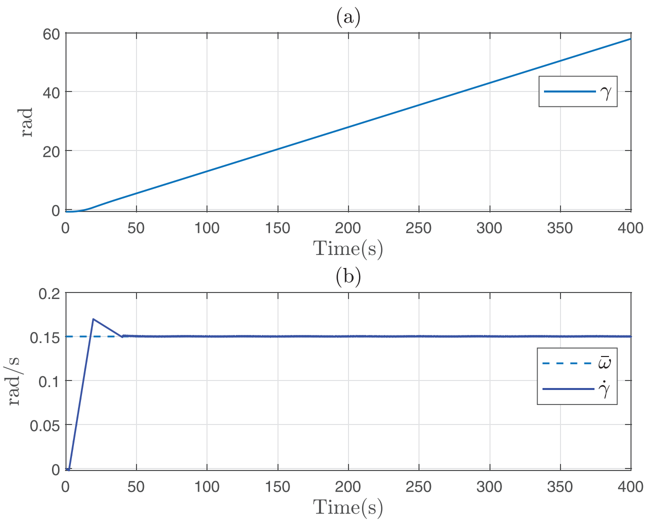

FIGURE 4 Coordination performance in case with single UAVs. (a) Time evolution of the path parameters. (b) Speeds of the path parameters.

The pursuit errors $\|e_i\|$ and the tracking radius ρ_i are depicted in Figures 6b and 6c, respectively. As shown in Figure 7, the path parameters of each UAV achieves consensus and evolves at a common expected speed. This means that the UAVs will converge to and remain within the desired circular formation and realizes the enclosing tracking of moving targets with unknown velocity. In summary, the proposed strategy can be finalized to complete the encirclement and tracking of moving targets under limited information (bearing-only measurement).

Finally, in order to show the superiority of the proposed scheme over the general schemes, a comparative experiments is added. The simulation parameters are chosen as $r_x = r_y = 10$, $\rho = 10$ m and $\bar{\omega} = 0.3$ rad/s. Besides, the target's trajectory is same as the scenarios of single UAV. The comparison results with [22] are shown in Figures 8 and 9. It is clear that although both of them can achieve the surround tracking of the target,

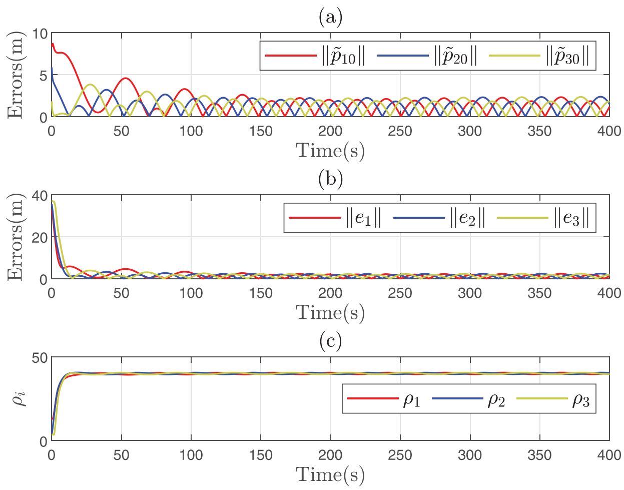

FIGURE 6 Simulation results. (a) Evolution of the estimation error of the relative target position by the UAVs. (b) Evolution of the encirclement errors. (c) Distance between UAVs and the moving target

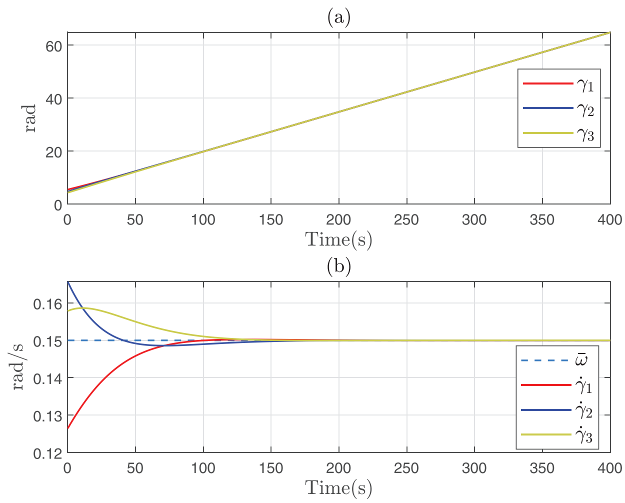

FIGURE 7 Cooperative performance of three UAVs. (a) Evolution of the path parameters. (b) Speeds of the path parameters.

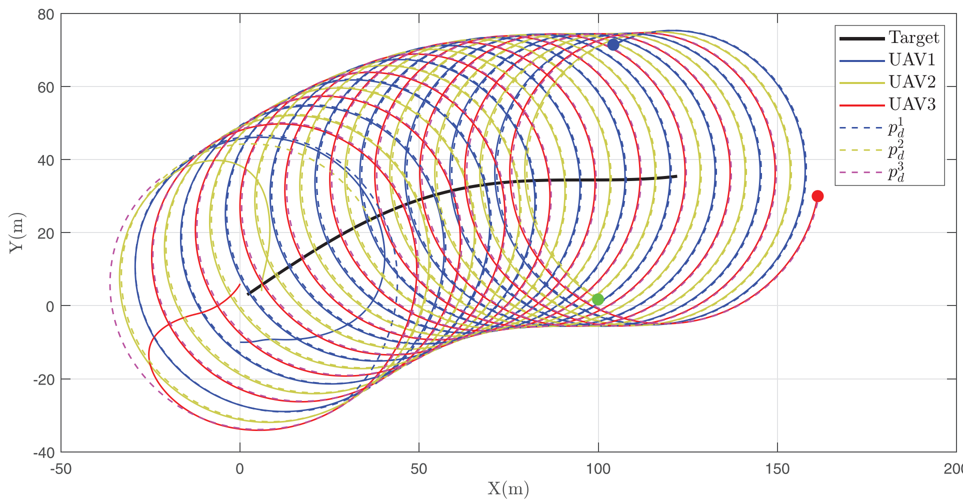

FIGURE 5 Trajectories of the target and three UAVs

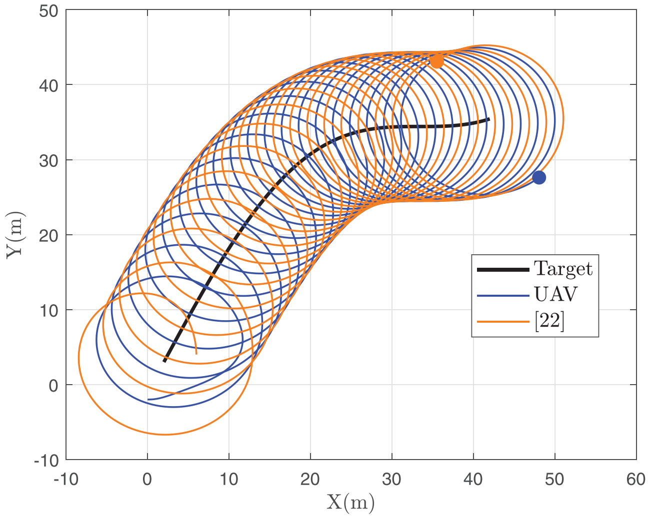

FIGURE 8 Trajectories of the target and the UAVs

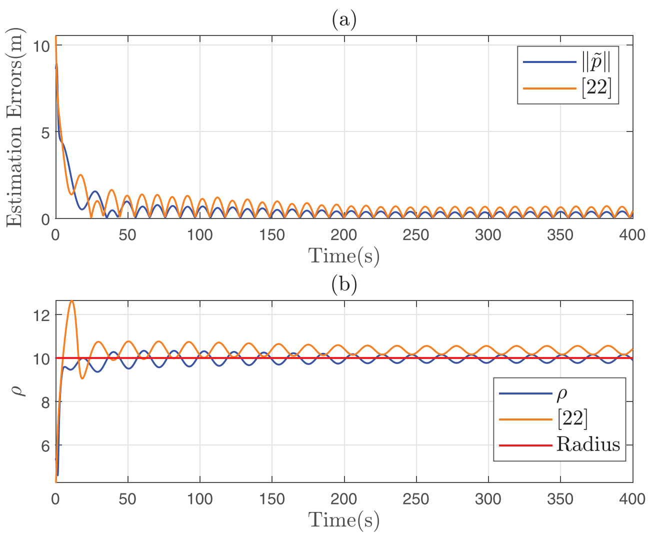

FIGURE 9 Simulation results. (a) Evolution of the estimation error of the relative target position by the UAVs. (b) Distance between the UAVs and the moving target

the proposed scheme is significantly better than [22] in terms of both the estimation accuracy and the tracking radius error.

5 | CONCLUSION

This paper investigates the localization and encirclement control of a moving target with unknown and bounded velocities by multi-UAVs. On the basis of only bearing measurements to the target, the target relative position estimator is designed. Furthermore, a distributed encirclement control algorithm based on CMPF is developed to make the multi-UAVs converge to a common circle with a specified radius around the target and also realize the required spacing mode along the circle. Theoretical analysis and simulation results verify the effectiveness of the design methods. Future work will address the robust CMPF problems in which multi-UAVs have constraints such as unknown wind disturbances, obstacle avoidance, communications restrictions and time delay.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

ORCID

Weizhen Wang https://orcid.org/0000-0003-4595-6527
Jiangbo Jia https://orcid.org/0000-0001-9869-399X

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