

A Cooperative Guidance Law for UAVs Target Tracking

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Abstract: - The problem of automatic tracking of ground targets is one of the important issues that UAVs need to face in task applications. The main concern of cooperative tracking is how to track a ground target and maintain the UAV formation simultaneously. In this paper, a new leader-follower formation is constructed to track a ground target. Firstly, a new leader UAV guidance law is proposed to track the ground target in the standoff mode, the stability is proved using a Lyapunov function. Secondly, new guidance laws for standoff tracking of the leader UAV and controlling of the inter-UAV angle of the circle formation are designed for follower UAVs, respectively, stabilities are also proved using two Lyapunov functions. Numerical simulation experiments show that the new leader-follower formation can track the static and moving targets well and its performance is better than the classic LVFG algorithm.

Key-Words: - UAV, Guidance Law, Ground Target, Cooperative Tracking, Stability.

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1 Introduction

In the past few decades, due to the rapid development of science and technology, the use of unmanned aerial vehicles (UAVs) in surveillance and reconnaissance, rescue and communication relay [1-3], etc., its application fields have been greatly expanded. At present, one of the most important applications of UAVs is the use of tracking ground targets, through the UAV guidance system, the target can be always in the field of view, so as to achieve real-time tracking purpose of ground targets [4-6]. Compared with single UAV, multi-UAV cooperative tracking can increase the coverage of the sensor on the ground target, reduce the target state estimation error, and it has a wider range of application prospects [7-8].

Unlike rotary-wing UAV, fixed-wing UAV must maintain a minimum speed to produce enough lift. A typical way to accomplish tracking mission is to monitor the ground target by orbiting around it at a desired distance, this tracking mode is called standoff tracking [9-10]. The guidance problem in cooperative standoff tracking can be divided into two aspects: relative distance control and inter-UAV angle control, which are realized by lateral and longitudinal guidance law respectively.

Lawrence et al [11] proposed a UAV lateral guidance law based on the Lyapunov vector field guidance (LVFG) method. Frew et al [12] assumed that the target was uniformly moving and the LVFG was compensated to improve the guidance accuracy of the relative distance, and another Lyapunov function was used to solve the flight velocity command as the longitudinal guidance law of the

UAV to control the inter-UAV angle. In [13], the weighted relative distance and inter-UAV angle error are used as the objective function, and the horizontal and vertical guidance commands for the next optimization step are searched by the method of model predictive control (MPC). While this method needs a lot of calculation time, there are still some difficulties to achieve online applications. In [14], a cyclic pursuit for coordinated target tracking applications based on sliding mode control and a virtual leader is proposed, but the guidance law is too complicated to achieve in practical projects. In [15], a variant cycle of standoff tracking applications is proposed, while only fixed and uniform moving targets were considered for this method. In [16], a new composite impact time control guidance law was proposed for simultaneous attack against a ground. In [17-19], the leader - follower formation guidance law were proposed in the presence of external disturbances.

From above previous work, we can conclude that the main problem of cooperative tracking is how to track the ground target and maintain the UAV formation simultaneously. In this paper, a new leader-follower formation tracking mode is proposed, which is based on the principle that a leader UAV is used to track a ground target in standoff mode, while multiple follower UAVs track the leader UAV and evenly distributed in a circle, the leader UAV and follower UAVs adopt the same tracking distance. As a result, the leader UAV maintains a certain distance from the ground target to avoid being exposed, while the follower UAVs can be closer to monitoring the ground target.

This paper is organized as follows: Section 1 describes the mathematical model of a ground target tracking problem. Section 2 provides the new guidance law of the leader UAV and mathematical stability proof. Section 3 provides the new guidance law of the follower UAVs and mathematical stability proof. The results of simulation are discussed in section 4. The paper ends with some conclusions.

2 Problem Formulation

In order to develop guidance law for the fixed-wing UAV that tracks a ground target, some assumptions have been stated. Firstly, the UAV is considered at a constant speed and a constant altitude over the ground. Furthermore, a separate inner loop (stabilization loop) and an outer loop (guidance loop) control approach is designed, similarly as in most applications [20-23].

In Fig.1, let ρ denotes the range between the UAV and the target, $\rho \geq 0$ and ρ is bounded. The bearing angle $\chi \in [0, 2\pi)$ is defined as the angle between the UAV forward direction and the direction from the UAV to the target, which measured counterclockwise. ρ_d denotes the desired radius, and v is the velocity of the UAV.

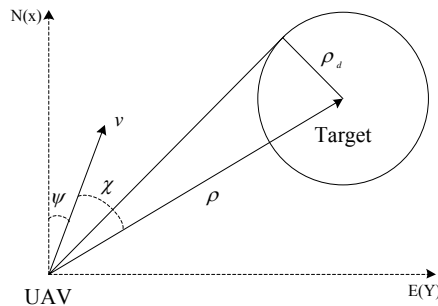


Fig.1. Geometry of tracking a stationary target.

The system dynamics can be described by the following kinematical model:

$$\begin{cases} \dot{x} = v \cos(\psi) \\ \dot{y} = v \sin(\psi) \\ \dot{\psi} = \omega \\ \dot{v} = u \end{cases} \quad (1)$$

where $[x, y]^T$ denotes the 2D location of the UAV, ψ denotes the heading angle, ω , u are the angular rate and acceleration as the control inputs to be

designed, respectively. $[x_t, y_t]^T$ denotes the 2D location of the target, then the range $\rho = \sqrt{(x - x_t)^2 + (y - y_t)^2}$. The objective is to design control input ω and u such that $\rho \rightarrow \rho_d$ as $t \rightarrow \infty$.

The dynamics (1) can be rewritten as:

$$\begin{cases} \dot{\rho} = -v \cos(\chi) \\ \dot{\chi} = \omega + \frac{v \sin(\chi)}{\rho} \\ \dot{v} = u \end{cases} \quad (2)$$

In dynamics (2), the state variables are changed from $[x, y, \psi]^T$ to $[\rho, \chi, v]^T$. Furthermore, it can be seen that if the velocity of the UAV is constant, $\dot{\rho}$ and χ can be determined by each other. When $\dot{\rho} = 0$, $\chi = \frac{\pi}{2}$ or $\frac{3\pi}{2}$, which represent the clockwise motion and counterclockwise motion of the UAV respectively.

3 Leader UAV guidance law design

Firstly, a guidance law of the leader UAV to track a static target is designed, and then the guidance law is expanded to track a moving target.

(1) static ground target tracking

In this paper, the guidance law for the leader UAV tracking a static ground target in standoff mode is designed as:

$$\begin{cases} \omega = kv \cos \chi - \frac{v \sin \chi}{\rho} - v(\rho - \rho_d) \\ u = 0 \end{cases} \quad (3)$$

Then we give the following conclusion.

Theorem 3.1: Consider UAV dynamics in (2) subject to the guidance law in (3). If $k > 0$, $(\rho_d, \frac{\pi}{2})^T$ is the asymptotically stable equilibrium point of the closed-loop system.

Proof:

Consider the following candidate Lyapunov function:

$$L_1 = 1 - \sin \chi + \frac{1}{2}(\rho - \rho_d)^2$$

It can be verified that $L_1 \geq 0$, and $L_1 = 0$ only at $(\rho_d, \frac{\pi}{2})^T$.

Taking the derivative of L_1 yields that

$$\dot{L}_1 = -\cos \chi \cdot \dot{\chi} + (\rho - \rho_d) \cdot \dot{\rho}$$

with (2), we have

$$\dot{L}_1 = v \cos \chi \cdot \left(-\frac{\omega}{v} - \frac{\sin \chi}{\rho} - \rho + \rho_d\right)$$

substitute ω into \dot{L}_1 , we have

$$\dot{L}_1 = -kv \cos^2 \chi.$$

Obviously, when $k > 0$, for any χ , there is $\dot{L}_1 \leq 0$ and it can be concluded that $\dot{L}_1 = 0$ if and only if $\chi = \frac{\pi}{2}$. Let $S = \{[\rho, \chi]^T \in R \times R \mid \chi = \frac{\pi}{2}\}$, when $L_1 = 0$, we can obtain that $\rho = \rho_d$, and no other solution can stay identically in S other than $(\rho_d, \frac{\pi}{2})^T$. According to La-Salle's invariance principle [24], $(\rho_d, \frac{\pi}{2})^T$ is the asymptotically stable equilibrium point of the closed-loop system.

(2) Constant speed ground target tracking

When the ground target moves at speed v_t , the UAV kinematics model can be written as:

$$\begin{cases} \dot{\rho} = -v \cos \chi + v_t \cos(\psi - \psi_t + \chi) \\ \dot{\chi} = \omega + \frac{1}{\rho}(v \sin \chi - v_t \sin(\psi - \psi_t + \chi)) \\ \dot{v} = u \end{cases} \quad (4)$$

the speed vector of the UAV can be decomposed into relative speed and the target speed vector: (depicted in fig.2)

$$\vec{v} = \vec{v}_m + \vec{v}_t \quad (5)$$

where \vec{v}_m is the relative speed vector. Then the dynamics in (4) can be rewritten as the relative motion:

$$\begin{cases} \dot{\rho} = -v_m \cos \chi_m \\ \dot{\chi}_m = \omega_m + \frac{1}{\rho} v_m \sin \chi_m \\ \dot{v}_m = u_m \end{cases} \quad (6)$$

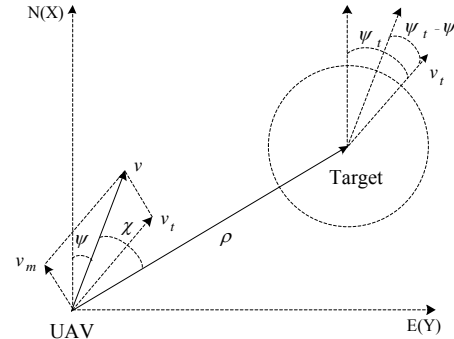


Fig.2. Geometry of tracking a moving target.

When the target is in uniform moving motion, v_t is constant. Let \vec{n}_m be the unit tangent vector of \vec{v}_m , and $\vec{\omega}$ be the angular velocity vector corresponding to \vec{v} , taking the derivative of (5) yields that

$$\vec{\omega} \times \vec{v} = \dot{v}_m \vec{n}_m + \vec{\omega}_m \times \vec{v}_m$$

take the norm of both sides, because $\dot{v}_m = (\vec{\omega} \times \vec{v}) \cdot \vec{n}_m$, thus we can obtain that

$$|\vec{\omega} \times \vec{v}|^2 = |(\vec{\omega} \times \vec{v}) \cdot \vec{n}_m|^2 + |\vec{\omega}_m \times \vec{v}_m|^2 \quad (7)$$

, we get

$$\omega^2 v^2 = \omega^2 v^2 \sin^2(\psi - \psi_m) + \omega_m^2 v_m^2$$

and

$$\omega_m^2 v_m^4 = \omega^2 [v^2 v_m^2 - |\vec{v} \times \vec{v}_m|^2]$$

According to the parallelogram law of the vector, the area of the two triangle which constituted by \vec{v} , \vec{v}_t and \vec{v} , \vec{v}_m are equal, that is

$$|\vec{v} \times \vec{v}_t| = |\vec{v} \times \vec{v}_m|$$

then we can obtain that

$$\omega_m^2 v_m^4 = \omega^2 [v^2 v_m^2 - |\vec{v} \times \vec{v}_t|^2]$$

we have

$$\omega_m = \frac{v\sqrt{v_m^2 - v_t^2} \sin(\psi_t - \psi)}{v_m^2} \omega$$

Finally, we can obtain the guidance law for tracking the constant speed ground target:

$$\left\{ \begin{array}{l} \omega = \frac{v_m^2 [kv_m \cos \chi_m - \frac{v_m \sin \chi_m}{\rho} - v_m(\rho - \rho_d)]}{v\sqrt{v_m^2 - v_t^2} \sin^2(\psi_t - \psi)} \\ u = 0 \end{array} \right. \quad (8)$$

the corresponding close-loop system can be written as

$$\left\{ \begin{array}{l} \dot{\rho} = -v_m \cos \chi_m \\ \dot{\chi} = \frac{v_m^2 [kv_m \cos \chi_m - \frac{v_m \sin \chi_m}{\rho} - v_m(\rho - \rho_d)]}{v\sqrt{v_m^2 - v_t^2} \sin^2(\psi_t - \psi)} + \frac{1}{\rho} v_m \sin \chi_m \\ \dot{v} = 0 \end{array} \right. \quad (9)$$

Then we give the following conclusion.

Theorem 3.2: Consider UAV dynamics in (4) subject to the guidance law in (8). If $k > 0$, $(\rho_d, \frac{\pi}{2})^T$ is the asymptotically stable equilibrium point of the closed-loop system in (9).

Proof:

Consider the following candidate Lyapunov function:

$$L_2 = 1 - \sin \chi_m + \frac{1}{2}(\rho - \rho_d)^2$$

Taking the derivative of L_2 yields that

$$\dot{L}_1 = -\cos \chi_m \cdot \dot{\chi}_m + (\rho - \rho_d) \cdot \dot{\rho}$$

substitute (6) and (8) into \dot{L}_2 , then

$$\dot{L}_2 = -kv \cos^2 \chi_m$$

Obviously, when $k > 0$, for any χ_m , we have $\dot{L}_2 \leq 0$, and only $\chi_m(t) = \frac{\pi}{2}$, there has $\dot{L}_2(t) = 0$. $\chi_m(t)$, $\rho(t)$ are both bounded, so $\dot{L}_2(t)$ is uniformly continuous, according to Barbalat's lemma [20], when $\dot{L}_2(t) \rightarrow 0$, $\chi_m(t) \rightarrow \frac{\pi}{2}$. Furthermore, because $\ddot{\chi}_m(t)$ is bounded, still according to Barbalat's lemma, we can conclude that when $\chi_m(t) \rightarrow 0$, $\rho(t) \rightarrow \rho_d$, $(\rho_d, \pi/2)^T$ is the asymptotically stable equilibrium point of the closed-loop system.

(3) Variable speed ground target

When the ground target moves at variable speed v_t , then v, v_m both are also variable, eq.(5) can be rewritten as the following scalar form:

$$\left\{ \begin{array}{l} v \cos \psi = v_m \cos \psi_m + v_t \cos \psi_t \\ v \sin \psi = v_m \sin \psi_m + v_t \sin \psi_t \end{array} \right.$$

Taking the derivative of both sides yields that

$$\left\{ \begin{array}{l} \dot{v} \cos \psi + v \dot{\psi} \cos \psi = \dot{v}_m \cos \psi_m + v_m \dot{\psi}_m \cos \psi_m \\ + \dot{v}_t \cos \psi_t + v_t \dot{\psi}_t \cos \psi_t \\ \dot{v} \sin \psi + v \dot{\psi} \sin \psi = \dot{v}_m \sin \psi_m + v_m \dot{\psi}_m \sin \psi_m \\ + \dot{v}_t \sin \psi_t + v_t \dot{\psi}_t \sin \psi_t \end{array} \right.$$

solving the quadratic equation and eliminate \dot{v}_m , we can obtain the guidance law for tracking the variable speed ground target:

$$\left\{ \begin{array}{l} \omega = \frac{1}{v \cos(\psi - \psi_m)} (v_m \omega_m + v_t \omega_t \cos(\psi_t - \psi_m)) \\ u = \dot{v}_t \frac{\sin(\psi_t - \psi_m)}{\sin(\psi - \psi_m)} \end{array} \right. \quad (10)$$

where

$$\omega_m = kv_m \cos \chi_m - \frac{v_m \sin \chi_m}{\rho} - v_m(\rho - \rho_d)$$

the corresponding close-loop system can be written as

$$\begin{cases} \dot{\rho} = -v_m \cos \chi_m \\ \dot{\chi} = \frac{1}{v \cos(\psi - \psi_m)} (v_m \omega_m + v_i \omega_i \cos(\psi_i - \psi_m)) + \frac{1}{\rho} v_m \sin \chi_m \\ \dot{\psi} = \dot{\psi}_i \frac{\sin(\psi_i - \psi_m)}{\sin(\psi - \psi_m)} \end{cases} \quad (11)$$

We can see that eq.(11) and eq.(9) are the same, thus still satisfy **Theorem 3.2** for variable speed ground target.

4 Follower UAV guidance law design

Consider N follower UAVs in the formation problem, the i -th ($i=1,2,\dots,N$) UAV's Dubins model can be written as:

$$\begin{cases} \dot{x}_i = v_i \cos(\psi_i) \\ \dot{y}_i = v_i \sin(\psi_i) \\ \dot{\psi}_i = \omega_i \\ \dot{v}_i = u_i \end{cases} \quad (i=1,2,\dots,N)$$

The geometry between the follower UAVs and the leader UAV is depicted in Fig.3.

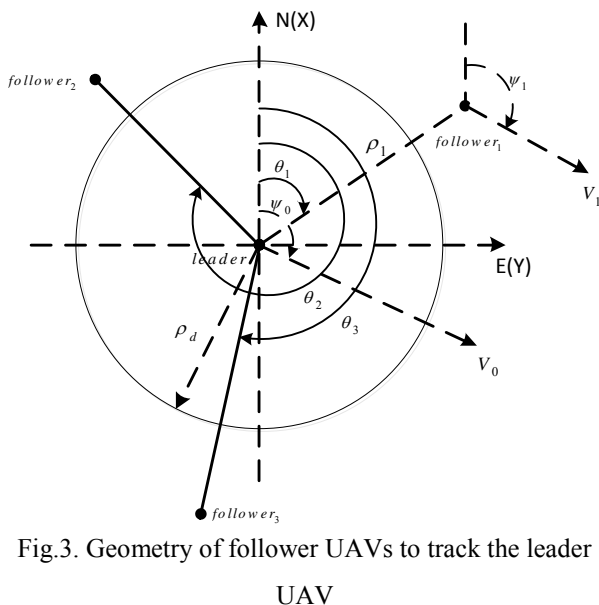


Fig.3. Geometry of follower UAVs to track the leader UAV

In this paper, the follower UAVs are required to maintain a circular formation centered at the leader UAV and hold equal angular separation. Meanwhile, the follower UAV's velocity and heading angle should gradually converge to the leader UAV's. The relative motion can be written as:

$$\begin{cases} \dot{\rho}_i = v_i \cos(\theta_i - \psi_i) - v_0 \cos(\theta_i - \psi_0) \\ \dot{\theta}_i = \frac{-v_i \sin(\theta_i - \psi_i) + v_0 \sin(\theta_i - \psi_0)}{\rho_i} \end{cases} \quad (12)$$

where the subscript '0' denotes the leader UAV.

The follower UAV's angular rate control is used to carry out distance and heading angle tracking for the leader UAV, while formation's inter-UAV angle control and velocity tracking are performed by speed control.

We use such a communication topology, that is, the follower UAVs can perceive the state of the leader UAV, and between the follower UAVs, a circular communication structure is applied.

(1) angular rate guidance law design

In this paper, the following angular rate guidance law is designed for the i -th follower UAV:

$$\omega_i = \dot{\psi}_0 - \frac{(\rho_i - \rho_d)}{(\psi_i - \psi_0)} \dot{\rho}_i - k_\omega (\psi_i - \psi_0) \quad (13)$$

Then we give the following conclusion.

Theorem 4.1: Consider the UAV formation dynamics in (12) subject to the guidance law in (13). If $k_\omega > 0$, the distance between the follower UAV and the leader UAV will gradually converge to ρ_d , the heading angle of the follower UAV will also gradually converge to the heading angle of the leader UAV.

Proof:

Consider the following candidate Lyapunov function:

$$L_\omega = \frac{1}{2} \sum_{i=1}^N [(\rho_i - \rho_d)^2 + (\psi_i - \psi_0)^2]$$

Taking the derivative yields that

$$\dot{L}_\omega = \sum_{i=1}^N [(\rho_i - \rho_d) \cdot \dot{\rho}_i + (\psi_i - \psi_0) \cdot (\dot{\psi}_i - \dot{\psi}_0)]$$

where $\dot{\psi}_i = \omega_i$, and

$$\dot{\omega}_i = \dot{\psi}_0 - \frac{(\rho_i - \rho_d)}{(\psi_i - \psi_0)} \cdot \dot{\rho}_i - k_\omega \cdot (\psi_i - \psi_0)$$

we get

$$\dot{L}_\omega = \sum_{i=1}^N (-k_\omega \cdot (\psi_i - \psi_0)^2) \leq 0$$

So $\psi_i - \psi_0$ is bounded, as \dot{L}_ω is uniformly continuous, $(\psi_i - \psi_0) \rightarrow 0$ according to Barbalat's lemma. Furthermore, as $\dot{\psi}_i - \dot{\psi}_0$ is uniformly continuous, we have $(\dot{\psi}_i - \dot{\psi}_0) \rightarrow 0$ according to Barbalat's lemma, then we can conclude that $\rho_i \rightarrow \rho_d$.

(2) velocity guidance law design

In this paper, the following velocity guidance law is designed for the i -th follower UAV:

$$u_i = \dot{v}_0 - \frac{(\Delta\theta - \frac{2\pi}{N})}{(v_i - v_0)} \Delta\dot{\theta} - k_v(v_i - v_0) \quad (14)$$

Then we give the following conclusion.

Theorem 4.2: Consider the UAV formation dynamics in (12) subject to the guidance law in (14), if $k_v > 0$, the inter-UAV angle between follower UAVs will gradually converge to $\frac{2\pi}{N}$, the speed of i -th follower UAV will gradually converge to the speed of the leader UAV.

Proof:

Consider the following candidate Lyapunov function:

$$L_u = \frac{1}{2} \sum_{i=1}^N [(\Delta\theta_i - \frac{2\pi}{N})^2 + (v_i - v_0)^2]$$

Taking the derivative yields that

$$\dot{L}_u = \sum_{i=1}^N [(\Delta\theta_i - \frac{2\pi}{N}) \cdot \Delta\dot{\theta}_i + (v_i - v_0) \cdot (\dot{v}_i - \dot{v}_0)]$$

where $\dot{v}_i = u_i$, and

$$u_i = \dot{v}_0 - \frac{(\Delta\theta_i - \frac{2\pi}{N})}{(v_i - v_0)} \Delta\dot{\theta}_i - k_v(v_i - v_0)$$

we get

$$\dot{L}_u = \sum_{i=1}^N (-k_v \cdot (v_i - v_0)^2) \leq 0$$

Similar with **Theorem 4.1**, we can also conclude that $\Delta\theta_i \rightarrow \frac{2\pi}{N}$ and $v_i \rightarrow v_0$.

5 Simulation Results

In this section, some simulation results are presented in order to demonstrate the effectiveness of the proposed leader-follower formation guidance laws. In these simulation cases, we consider a 4-UAVs formation as an example, UAV #0 is the leader UAV, UAV #1-UAV #3 are the follower UAVs. The ground target motion is considered as stationary, linear with constant speed, linear with variable speed, respectively.

Firstly, the simulation applies the leader UAV to track a ground target, then the UAV formation to track the ground target in the same way.

(1) Track a ground target using one UAV

The initial states of the UAV are set as follows:

- Position coordinate : (800,0)
- Heading angle : -60°
- Cruising speed : 45 m/s
- Maximum heading angular rate : 0.1 rad/s

The initial states of the ground target are set as follows:

- Position coordinate : (1000,1500)
- Heading angle : 30°
- Speed : 15m/s

The gain is chosen as: $k = 0.0025$.

a. Static ground target

Trajectories of the UAV are shown in Fig.4, the convergence curves of bearing angle and relative range are shown in Fig.5.

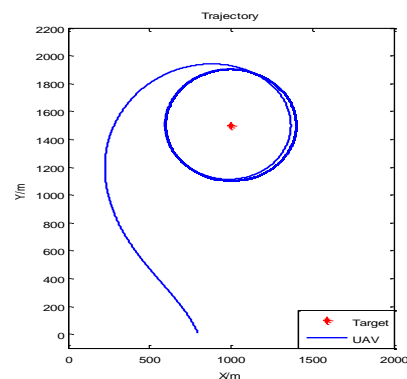
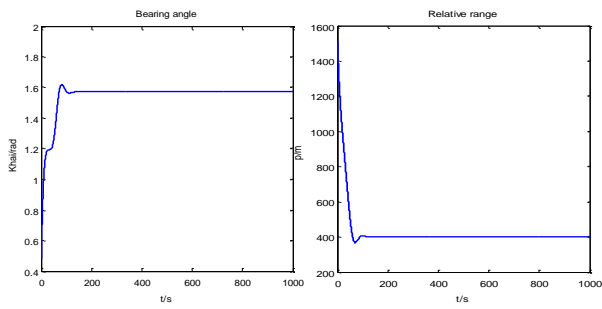


Fig.4. Trajectory of tracking a static target



a. Bearing angle b. Relative range

Fig.5. Bearing angle and relative range of tracking a static target

b. Constant speed ground target

Trajectories of the UAV and the ground target are shown in Fig.6, the convergence curves of bearing angle and relative range are shown in Fig.7.

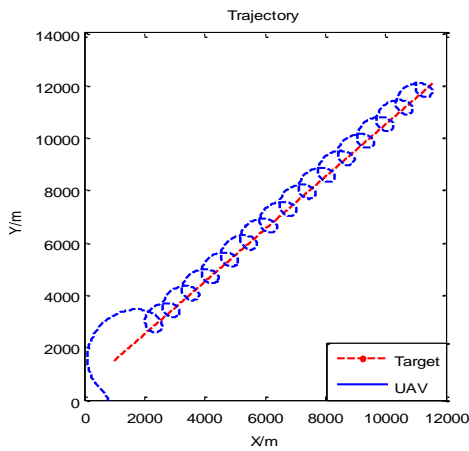
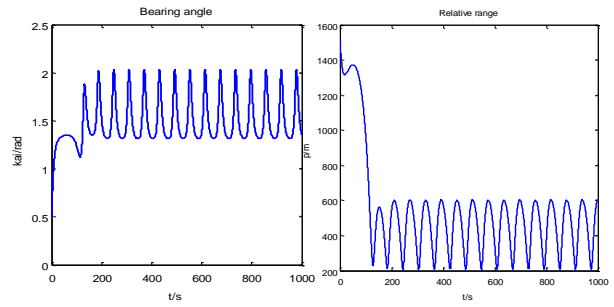


Fig.6. Trajectory of tracking a constant speed target



a. Bearing angle b. Relative range

Fig.7. Bearing angle and relative range of tracking a constant speed target

c. Variable speed ground target

The speed of ground target is set as:

$$v_t = 12 + 2 \times \sin(t/10)$$

The angular velocity of ground target is set as:

$$\dot{\psi}_t(t) = \begin{cases} -0.005 & t < 400 \\ 0 & 400 \leq t \leq 600 \\ 0.005 & t > 600 \end{cases}$$

Trajectories of the UAV and the ground target are shown in Fig.8, the convergence curves of bearing angle and relative range are shown in Fig.9.

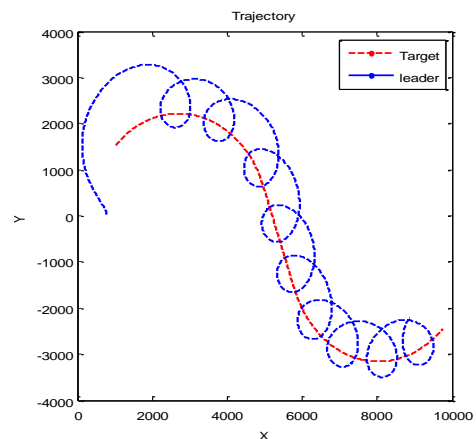


Fig.8. Trajectory of tracking a variable speed target

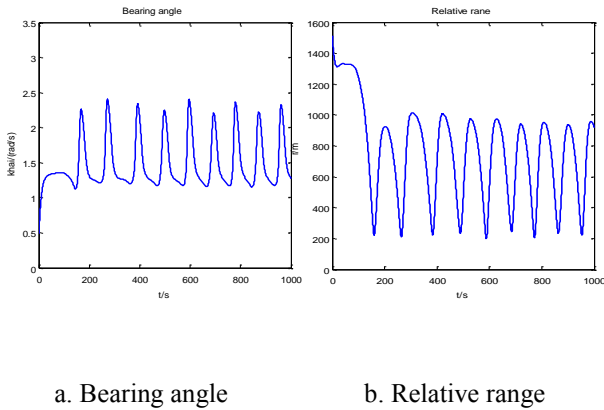


Fig.9. Bearing angle and relative range of tracking a variable speed target

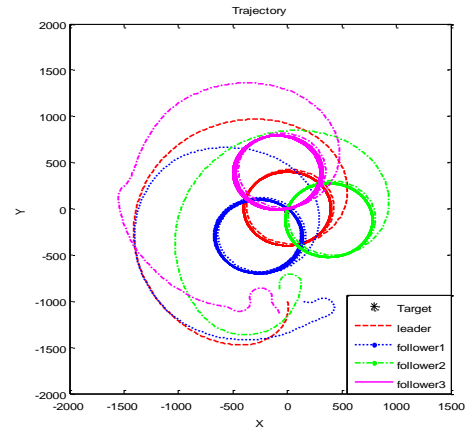


Fig.10. Trajectory of cooperative tracking a static target

From Fig. 4 to Fig.9, it can be seen that regardless of the ground target is static or moving, the UAV always can track the ground target well in a standoff mode.

(2) Track a ground target using formation UAVs
 The initial states of the UAV #1 are set as follows:

- Position coordinate : (150, -1000)
- Heading angle : -30°
- Cruising speed : 40.5 m/s
- Maximum heading angular rate : 0.1 rad/s

The initial states of the UAV #2 are set as follows:

- Position coordinate : (-75, -870)
- Heading angle : 80°
- Cruising speed : 41 m/s
- Maximum heading angular rate : 0.1 rad/s

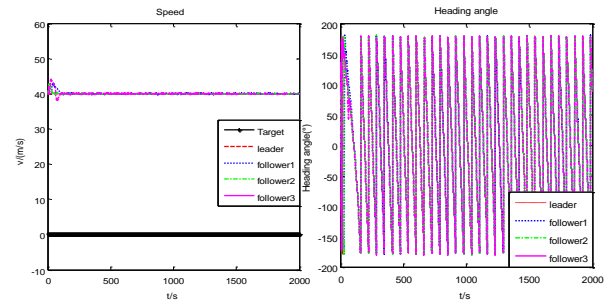
The initial states of the UAV #3 are set as follows:

- Position coordinate : (-75, -1130)
- Heading angle : 100°
- Cruising speed : 40.5 m/s
- Maximum heading angular rate : 0.1 rad/s

The gains are chosen as: $k_v = 1.28, k_\omega = 1.2$.

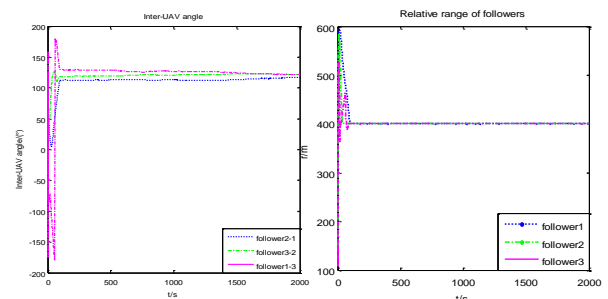
a. Static ground target

Trajectories of the formation are shown in Fig.10, the speed and heading angle of the formation are shown in Fig.11, the inter-UAV angle and relative range between leader and follower UAVs are shown in Fig.12.



a. Speed of target and b. heading angle of UAVs

Fig.11. Speed and heading angle of cooperative tracking a static target



a. Inter-UAV angle between follower UAVs b. Relative range between leader and follower

UAVs

Fig.12. Inter-UAV angle and relative range of cooperative tracking a static target

b. Constant speed ground target

Trajectories of the formation are shown in Fig.13, the speed and heading angle of the formation are shown in Fig.14, the inter-UAV angle and relative range between leader and follower UAVs are shown in Fig.15.

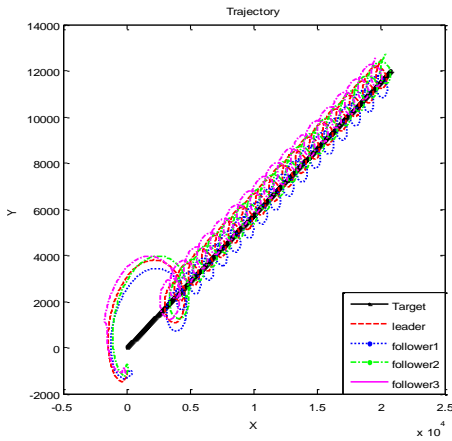
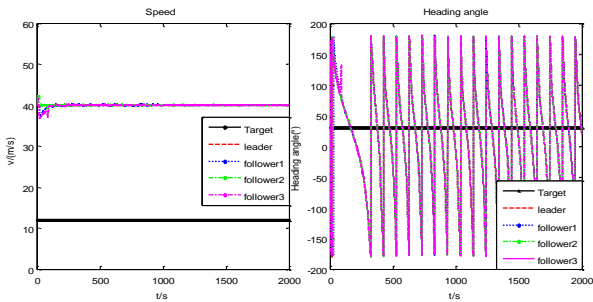
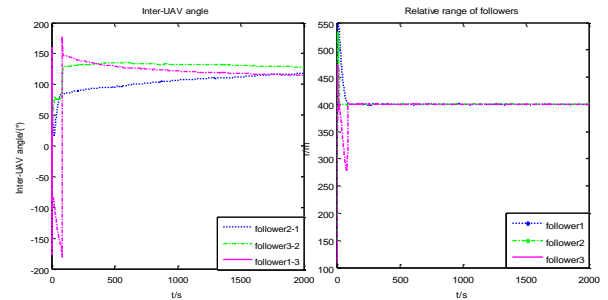


Fig.13. Trajectory of cooperative tracking a constant speed target



a. Speed of target and UAVs b. heading angle of UAVs

Fig.14. Speed and heading angle of cooperative tracking a constant speed target



a. Inter-UAV angle between follower UAVs b. Relative range between leader and follower UAVs

Fig.15. Inter-UAV angle and relative range of cooperative tracking a constant speed target

c. Variable speed ground target

Trajectories of the formation are shown in Fig.16, the speed and heading angle of the formation are shown in Fig.17, the inter-UAV angle and relative range between leader and follower UAVs are shown in Fig.18.

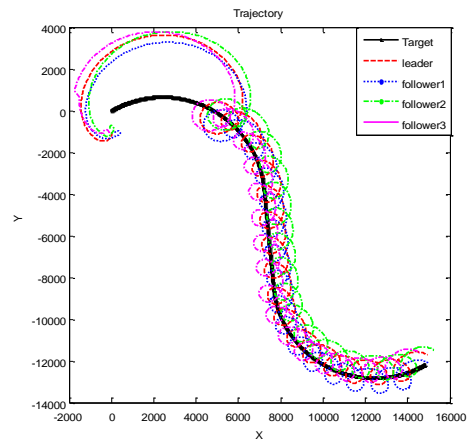


Fig.16. Trajectory of cooperative tracking a variable moving target

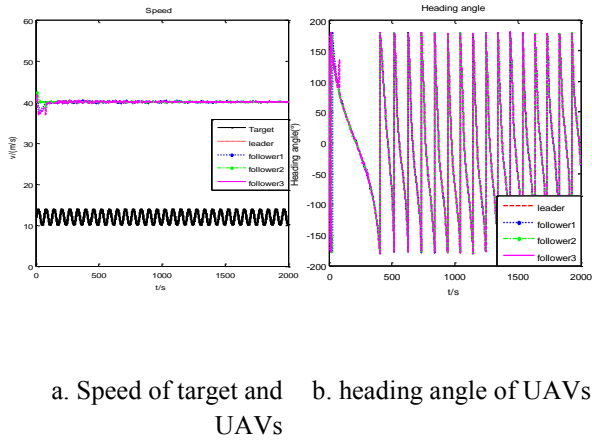


Fig.17. Speed and heading angle of cooperative tracking a variable speed target

[12] to run the same simulation case of variable speed ground target tracking. We choose the tracking performance of UAV #1 as an example.

The speed of UAV #1 and relative range between UAV #1 and the ground target using proposed method in this paper and literature [12] are shown in Fig.19.

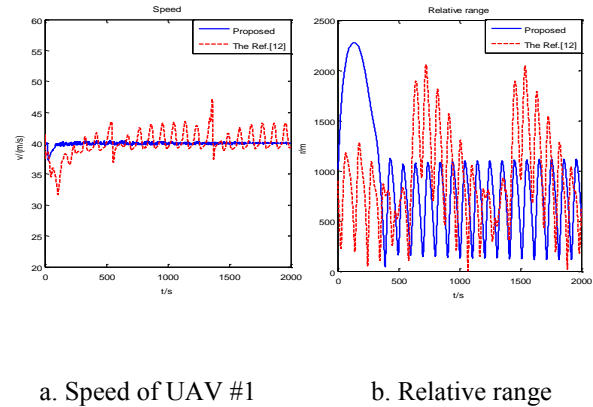


Fig.19. Speed of UAV #1 and relative range

When other performances are relative equivalent, from Fig. 19, the proposed guidance law in this paper makes the speed and heading angle of the follower UAVs always be consistent with the leader UAV, thus the convergence characteristics of speed and relative range of the UAV #1 are better than the results in Ref.[12].

5 Conclusion

In this paper, a new leader-follower formation tracking scheme is proposed, which is based on the principle that a leader UAV is applied to track a ground target in standoff mode, while multiple follower UAVs to track the leader UAV and evenly distributed in a circle. As a result, the leader UAV maintains a certain distance to the ground target from avoid being exposed, while the follower UAVs can be closer to monitoring the ground target. The stabilities of the new guidance laws are proved using Lyapunov functions. Numerical simulations of a 4-UAVs formation show that the new leader-follower formation can track the static and moving targets well and its performance is better than the well-known classic LVFG algorithm.

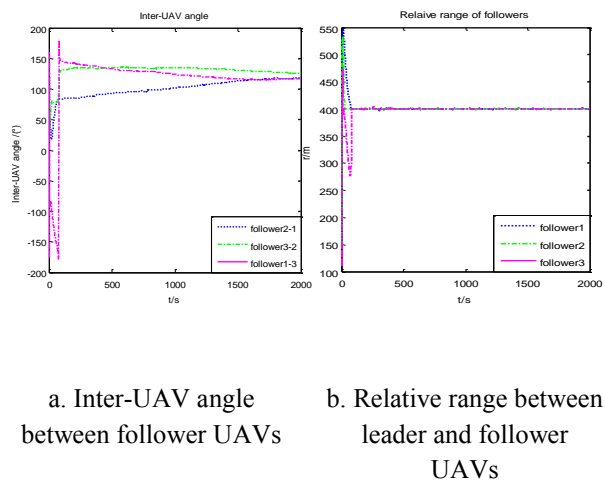


Fig.18. Inter-UAV angle and relative range of cooperative tracking a variable speed target

From Fig. 10 to Fig.18, it can be seen that regardless of the ground target is static or moving, the desired formation always can be achieved , the follower UAV's velocity and heading angle gradually converge to the leader UAV's, and the UAV formation always can track the ground target well.

(3) Simulation analysis and comparison

In order to further analyze and verify the tracking performance, we adopt the well-known LVFG guidance algorithm proposed in literature

References

- [1] Wu Mintang, Fei Yuhua, *Flight control system* [M]. Beijing: Beijing University of Aeronautics and Astronautics Press, 2005: 46-64.
- [2] S Rathinam, Zu W K, R Sengupta. Vision-Based Monitoring of Locally Linear Structures Using an Unmanned Aerial Vehicle[J].*Journal of Infrastructure Systems*,2008,14(1):52-63.
- [3] WANG Daobo, WANG Yin, JIANG Wanyue et al. Path planning of multi-UAV ground moving target based on chemical reaction optimization [J]. *Science in China*: 2015, 45 (6): 583-594
- [4] John T. Betts. Survey of Numerical Methods for Trajectory Optimization [J]. *Journal of Guidance, Control, and Dynamics*, 2008, 21(2):193-207.
- [5] Dobrokhodov V N. Vision-based tracking and motion estimation for moving targets using small UAVs[J]. *Journal of Guidance Control & Dynamics*, 2006, 31(4):907-917.
- [6] Kim Z W, Sengupta R. Target detection and position likelihood using an aerial image sensor[C]// *IEEE International Conference on Robotics and Automation*, 2008.
- [7] Kim Y, Sugie T. Cooperative control for target-capturing task based on a cyclic pursuit strategy. *Automatica*, 2007, 43(08): 1426-1431.
- [8] Daingri S, Sinha A. Nonlinear cyclic pursuit based cooperative target monitoring [C]// *International symposium on distributed autonomous robotic systems*, Baltimore, MD, Nov 2012.
- [9] Bertuccelli L F, How J P. Search for dynamic targets with uncertain probability maps[C]// *IEEE American Control Conference*, 2006.
- [10] Zhiyuan Li, Naira Hovakimyan, Vladimir Dobrokhodov and Isaac Kammer. Vision-based Target Tracking and Motion Estimation Using a Small UAV[C]. *IEEE conference on Decision and Control*, 2010.
- [11] Lawrence D A, Frew E W, Pisano W J. Lyapunov vector fields for autonomous unmanned aircraft flight control[J]. *Journal of Guidance Control and Dynamics*, 2012, 31(31):1220-1229.
- [12] Frew E W, Lawrence D A, Steve M. Coordinated standoff tracking of moving targets using Lyapunov guidance vector fields[J]. *Journal of Guidance Control and Dynamics*, 2008, 31(2):290-306.
- [13] Kim S, Oh H, Tsourdos A. Nonlinear model predictive coordinated stand off tracking of a moving ground vehicle[J]. *Journal of Guidance, Control and Dynamics*, 2013, 36(2):557-566.
- [14] Zhang M, Liu H H T. Cooperative tracking a moving target using multiple fixed-wing UAVs[J]. *Journal of Intelligent and Robotic Systems*, 2016, 81(3):505-529.
- [15] Hashemi A, Cao Y, Casbeer D W, et al. Unmanned aerial vehicle circumnavigation using noisy range-based measurements without global positioning system information[J]. *Journal of Dynamic Systems Measurement & Control*, 2015, 137(3):1-10.
- [16] Z.T Cheng, Bo Wang, Lei Liu, et al. A composite impact-time-control guidance law and simultaneous arrival. *Aerospace Science and Technology*[J]., 80 (2018) 403-412.
- [17] N Zhang, W.D Gai, G.L Zhang, et al. An active disturbance rejection control guidance law based collision avoidance for unmanned aerial vehicles. *Aerospace Science and Technology* [J], 77 (2018) 658-669.
- [18] L.L He, P Bai b, X.L Liang , et al. Feedback formation control of UAV swarm with multiple implicit leaders. *Aerospace Science and Technology*[J]., 72 (2018) 327-334.
- [19] X.L Ai, J.Q Yu. Flatness-based finite-time leader-follower formation control of multiple quadrotors with external disturbances. *Aerospace Science and Technology* [J], 92 (2019) 20-33.
- [20] Cao Y. UAV circumnavigating an unknown target under a GPS-denied environment with range-only measurements [J]. *Automatica*, 2014, 55(C):150-158.
- [21] Cao Y. UAV circumnavigating an unknown target using range measurement and estimated

range rate[C]// *IEEE American Control Conference*, 2014.

[22] Varga M, Zufferey J C, Heitz G H M, et al. Evaluation of control strategies for fixed-wing drones following slow-moving ground agents[J]. *Robotics and Autonomous Systems*, 2015, 72(1):285-294.

[23] Regina N, Zanzi M. UAV guidance law for ground-based target trajectory tracking and loitering[C]// *IEEE Aerospace Conference*, 2011.

[24] KHALIL H K. *Nonlinear systems*[M]. 3rd ed. Upper Saddle River: Prentice Hall, 2002: 139-144.

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