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Control System Design for an Unmanned Helicopter to Track a Ground Target

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Abstract: Due to potential wide applications, the problem of utilizing an unmanned helicopter to track a ground target has become one of the most active research directions in related areas. However, in most cases, it is possible for a dynamic target to implement evasive actions with strong maneuverability, such as a sudden turn during high-speed movement, to flee from the tracker, which then brings much difficulty for the design of tracking control systems. Currently, most research on this field focuses on utilizing a ground mobile robot to track a high-speed target. Unfortunately, it is very difficult to extend those developed methods to airborne applications due to much more complex dynamices of UAV-target relative motion. This study investiages thoroughly for the problem of using an unmanned helicopter to track a ground target, with particular emphasis on the avoidance of tracking failure caused by the evasive maneuvers of dynamic targets. Specifically, a novel control scheme, which consists of an innovative target tracking controller and a classical flight controller, is proposed for the helicopter-target tracking problem. Wherein, the tracking controller, whose design is the focus of the paper, aims to utilize the motion information of the helicopter and the dynamic target to construct a suitable trajectory for the helicopter, so that when it flies along this trajectory, the relative pose between the helicopter and the dynamic target will be kept consant. When designing the target tracking controller, a novel coordinate transformation is firstly introduced to convert the tracking system into a more compact form convenient for control law design, the desired velocities for the helicopter is then proposed with consideration of the dynamic constraint. The stability of the closed-loop system are finally analyzed by Lyapunov techniques. Based on Matlab/Simulink environment, two groups of simulation are conducted for the helicopter-target tracking control system where the target moves along a linear path and takes a sudden turn during high-speed movement, respectively. As shown by the simulation results, both the distance error and the pointing error are bounded during the tracking process, and they are convergent to zero when the target moves straightly. Moreover, the tracking performance can be adjusted properly to avoid tracking failure due to evasive maneuvers of the target, so that to guarantee superior tracking performance for all kinds of dynamic targets.

Key words: unmanned helicopter, trajectory plan, target tracking

1 Introduction

Unmanned Aerial Vehicles (UAVs) have been an active area of research in recent years[1–2], due to the reason that they are indispensable for various applications where human intervention is either impossible, risky or costly, such as hazardous material recovery, disaster relief support, and so on. Helicopter is a highly maneuverable and versatile UAV platform presenting the following flexibility: it can take off and land vertically, hover in place, perform longitudinal and lateral flight as well as drop and retrieve objects from otherwise inaccessible places[3–4].

Owing to its flexibility, a helicopter has been regarded as an ideal choice to implement such tasks as traffic monitoring, military reconnaissance, infrastructure inspection, mine detection, search-and-rescue, and so on. Subsequently, the problem of utilizing an unmanned helicopter to track a ground target has appeared to be a very promising research direction due to potential wide applications. Therefore, it has recently received more and more attention and gradually become a topic of considerable interest over the past few years[5–6]. Visual sensing is often used to estimate the position and velocity of features in the image plane (urban features like windows) in order to generate velocity references for the flight control. In Ref. [7], a notable vision-based technique referred to as visual odometer is utilized to estimate helicopter position by visually locking on and tracking stationary objects on the ground. In Ref. [8], the authors proposed a vision-based approach to detect and track features in an urban environment. To solve the problem of autonomous landing, in Ref. [9], the authors presented the design and implementation of a real-time, vision-based landing algorithm for an autonomous helicopter.

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Specifically, the helicopter updates its landing target parameters based on vision information and uses an onboard behavior-based controller to follow a path to the landing site. In Ref. [10], the authors presented the design of an optimal trajectory controller to land a helicopter on a moving target. Specifically, a kinematic model is utilized to derive an optimal controller to make the helicopter track an arbitrarily moving target and then land on it. In Ref. [11], the authors proposed a generally applicable method for the tracking of ground vehicles by aerial vehicles. Unfortunately, the targets to be tracked in the researches mentioned above are either completely static or slow in motion. Yet, in the context of most applications, it is highly possible that a target presents complex dynamic behavior, such as high-speed, evasive actions, and so on. In this case, further research is required to improve the performance of the tracking controller.

Recently, researchers have focused their effort on the problem of maneuver target tracking by using ground mobile robots, and many results have been reported in robotics literature[12–15]. Unfortunately, these techniques cannot be easily extended to airborne applications due to highly dynamic UAV-target relative motion.

From the literature survey, we note that the challenge for dynamic target tracking system is to develop an advanced control law for the helicopter so that it trackes the target based on a stability criterion. This observation motivates us to design a new method to address the problem of tracking failure caused by evasive maneuvers of the target. Specifically, we intend to design a two-level control scheme for the target tracking problem. On the higher lever, the states of the target and the helicopter are used to compute a desired trajectory for the helicopter. On the lower lever, the helicopter is controlled by the flight controller so as to follow the desired trajectory. Classical control method (PID-based feedback control) is adopted for the helicopter flight control due to the reason that it is simple and intuitive, and more importantly, its effectiveness has been validated in numerous flight tests. In order to avoid tracking failure due to evasive maneuvers by the target, a novel input transformation is firstly introduced to simplify the tracking system, so that to set up a direct relationship between the tracking objectives and the desired velocities of the helicopter. Based on that, various tracking trajectories are then generated for the autonomous helicopter to meet the tracking requirements. When following these trajectories, the helicopter can not only track the ground target with the given relative position and orientation, but also fly at a relatively safe manner to avoid possible tracking failure due to evasive maneuvers of the target.

The remainder of the paper is organized as follows. Section 2 clarifies the target tracking problem considered in this paper and exhibits a general description for the control scheme. In section 3, the process of target tracking controller design is represented, and the associated stability properties are rigorously analyzed. Extensive simulation results are provided in section 4 to verify the superior performance of the proposed approach. Finally, some conclusions are given in the last section.

2 Problem Formulation

2.1 Problem statement

As shown in Fig. 1, the tracking problem in this paper requires an unmanned helicopter flying at a constant altitude to track a ground target with a fixed relative position and orientation. The target to be tracked is subject to a nonholonomic constraint, such as a car. For the purpose of escaping, the target may move at a high speed or take a sudden turn simultaneously. To estimate the states of the moving target, a pan-tilt platform which carries a monocular camera is mounted on the helicopter.

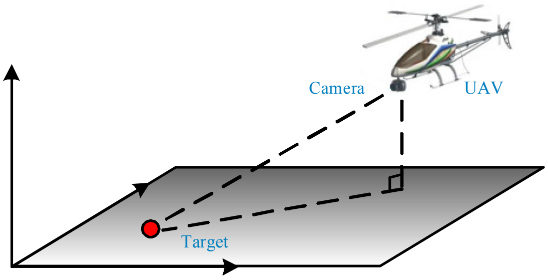

Fig. 1. Vision-based ground target tracking system

2.2 General description of the control scheme

To enable the helicopter to achieve stable tracking for a ground target, we need to design a control method to implement the following two sub-tasks: 1. Keeping the horizontal distance between the target and the helicopter as a constant by controlling the flight trajectory; 2. Making the heading of the helicopter point to the target Simultaneously.

Considering the dynamic properties of the helicopter and the control objective, we propose a control scheme which contains a two-level structure outlined in Fig. 2. On the higher lever, the states of the target and the helicopter are used to compute a desired trajectory driving the helicopter to track the target. On the lower lever, the helicopter is controlled so that it follows the desired trajectory. As shown in the diagram, there are two important blocks in the control scheme, namely target tracking controller and flight controller. A classical control law combined of PID and fuzzy controller is utilized as the flight controller (see Ref. [16] for details about the flight controller). This paper mainly focuses on the design of the target tracking controller.

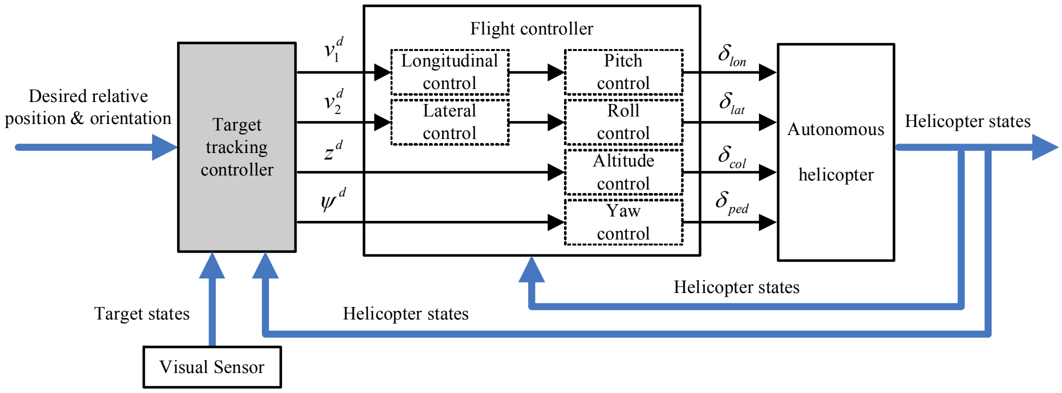

Fig. 2. Block diagram of the proposed approach

2.3 Problem definition

Since the flight altitude is a constant, the tracking problem can be simplified on the *XY* plane. Refer to Fig. 3 for the relevant geometric relationship and the definition of auxiliary variables. Let $\boldsymbol{d}$ be the distance vector from the helicopter to the target, with θ_1 denoting its orientation. Then $\|\boldsymbol{d}\|$ and θ_1 can be computed as follows:

$$\|\boldsymbol{d}\| = \sqrt{(x-x_t)^2+(y-y_t)^2}\ , \tag{1}$$

$$\theta_1 = \arctan\left(\frac{y-y_t}{x-x_t}\right), \tag{2}$$

where (x,y) and (x_t,y_t) denote the position of the helicopter and the target, respectively.

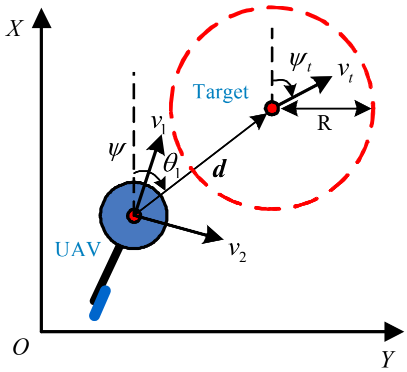

Fig. 3. Geometric relationship

The kinematic model of the helicopter is given by

$$\begin{cases} \dot{x} = v_1\cos\psi - v_2\sin\psi, \\ \dot{y} = v_1\sin\psi + v_2\cos\psi, \\ \dot{\psi} = \omega, \end{cases} \tag{3}$$

where ψ represents the heading of the helicopter, v_1 and v_2 denote the longitudinal and lateral velocities, and ω is the yaw angle rate. The kinematic model of the target is given by

$$\begin{cases} \dot{x}_t = v_t\cos\psi_t, \\ \dot{y}_t = v_t\sin\psi_t, \\ \dot{\psi}_t = \omega_t, \end{cases} \tag{4}$$

where ψ_t denotes the orientation of the target, v_t and ω_t are the linear and angular velocities.

2.4 Error system development

Before the error system development, we make the following reasonable assumption.

Assumption 1. Initially, the UAV does not contact with the target, that is, $\|\boldsymbol{d}(t_0)\| > 0$.

Based on the control objective, we construct the control error as follows:

$$\begin{cases} e_1 = R - \|\boldsymbol{d}\|, \\ e_2 = \theta_1 - \psi, \end{cases} \tag{5}$$

where R denotes the desired distance between the target and the helicopter, e_1 and e_2 represents the distance and orientation error, respectively (see Fig. 3).

After taking the time derivative of Eq. (5), substituting Eqs. (1) and (2) into the resulting expression, we have

$$\begin{pmatrix} \dot{e}_1 \\ \dot{e}_2 \end{pmatrix} = \boldsymbol{B}\begin{pmatrix} \dot{x}-\dot{x}_t \\ \dot{y}-\dot{y}_t \end{pmatrix} - \begin{pmatrix} 0 \\ \omega \end{pmatrix}, \tag{6}$$

where matrix $\boldsymbol{B} \in \Re^{2\times 2}$ is defined as

$$\boldsymbol{B} = \begin{pmatrix} \cos\theta_1 & \sin\theta_1 \\ \dfrac{\sin\theta_1}{\|\boldsymbol{d}\|} & -\dfrac{\cos\theta_1}{\|\boldsymbol{d}\|} \end{pmatrix}. \tag{7}$$

After substituting Eqs. (3) and (4) into Eq. (6), we obtain the following open-loop dynamics for the error system:

$$\begin{pmatrix} \dot{e}_1 \\ \dot{e}_2 \end{pmatrix} = \boldsymbol{A}\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} - \begin{pmatrix} 0 \\ \omega \end{pmatrix} - \boldsymbol{B}\begin{pmatrix} v_t\cos\psi_t \\ v_t\sin\psi_t \end{pmatrix}, \tag{8}$$

where the matrix $\boldsymbol{A} \in \Re^{2\times 2}$ is defined as

$$\boldsymbol{A} = \begin{pmatrix} \cos e_2 & \sin e_2 \\ \dfrac{\sin e_2}{\|\boldsymbol{d}\|} & -\dfrac{\cos e_2}{\|\boldsymbol{d}\|} \end{pmatrix}. \tag{9}$$

Clearly, the determinant of $\boldsymbol{A}$ is $-\|\boldsymbol{d}\|^{-1}$.

Remark 1. Based on the fact that $\|\boldsymbol{d}(t_0)\| > 0$ (see **Assumption 1**), and the subsequent stability analysis, we can show that the distance between the target and the helicopter is maintained in a pre-specified region. Thus $\boldsymbol{A}$ is always invertible.

Further, to describe the alignment error, we define the following error signal:

$$e_3 = \psi_t - \theta_1.$$

Assumption 2. The initial orientation of the helicopter relative to the target satisfies: $|e_3(t_0)| < \dfrac{\pi}{2}$.

Assumption 3. The target being tracked moves with unknown velocity satisfying the condition of $v_t > 0$.

Before proceeding with the description of the complete control scheme, it should be pointed out that the controller design is presented in a complete information context. Specifically, to estimate the states of the helicopter, the sensory data of three inertial sensors, three gyroscopic sensors, and three magnetometer sensors are combined in an Altitude and Heading Reference System (AHRS), which are further merged with the GPS signals by a Kalman filter. For target states estimation, images of the target are first utilized to estimate its position and velocity in the image plane, which is then fused with the on-board sensors to estimate its states in the world coordinate.

3　Target Tracking Controller Design

The control objective is to drive e_1 and e_2 to zero by using the helicopter longitudinal velocity v_1, lateral velocity v_2 and the yaw angle rate ω as control inputs. At the same time, it is required to optimize the tracking trajectory to guarantee lower control effort. Furthermore, the generated trajectory is required to satisfy the physical constraint of the helicopter, so that to avoid possible tracking failure caused by evasive maneuvers of the target. For instance, when the target takes any sudden turn during the high-speed movement, a carelessly designed trajectory will make the helicopter present some undesired lateral motion due to the centrifugal effect during the tracking process, which will finally result in tracking failure.

3.1　Input transformation

For the sake of facility, we first introduce an input transformation to convert the error system into a more compact form. To this end, based on the structure of the error dynamics of Eq. (9), we proposed the following control law to compensate for the nonlinearities of the system:

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \boldsymbol{A}^{-1} \cdot \begin{pmatrix} v_d \\ \omega_1 \end{pmatrix} + \boldsymbol{A}^{-1} \cdot \boldsymbol{B} \cdot \begin{pmatrix} v_t \cos\psi_t \\ v_t \sin\psi_t \end{pmatrix}, \tag{10}$$

where the state information of the target, including v_t and ψ_t, is obtained from the on-board camera and other equipped sensors, $[v_d, \omega_1]^{\mathrm{T}}$ denotes the virtual control vector which will be subsequently designed to construct a suitable trajectory for the helicopter. Refer to Fig. 4 for the geometric signification of v_d and ω_1, then we have

$$\begin{cases} v_d = \|\dot{\boldsymbol{d}}\|, \\ \omega_1 = \dot{\theta}_1. \end{cases}$$

Thus, once the virtual control input $[v_d, \omega_1]^{\mathrm{T}}$ is designed, the control input $[v_1, v_2]^{\mathrm{T}}$ can be computed from Eq. (10). After substituting Eq. (10) into Eq. (8), we can rewrite the open-loop dynamics of the error system as follows:

$$\begin{cases} \dot{e}_1 = v_d, \\ \dot{e}_2 = \omega_1 - \omega. \end{cases} \tag{11}$$

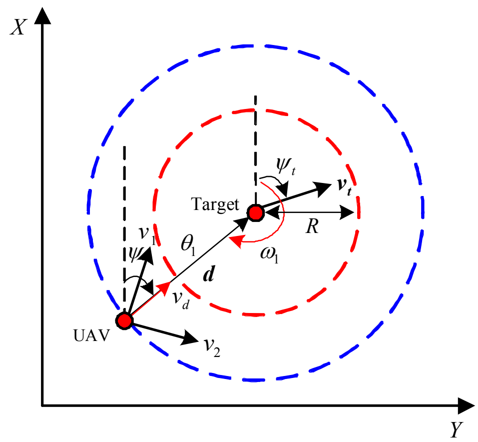

Fig. 4.　Input transformation with definition of some relevant variables

3.2　Controller design

Based on the error system of Eq. (11) and the subsequent stability analysis, we proposed the following control law for the helicopter:

$$\begin{cases} v_d = -k_1 e_1 - k_1 f_1(\gamma), \\ \omega_1 = v_t (R - e_1)^{-1} \sin e_3 + g(\cdot), \\ \omega = v_t (R - e_1)^{-1} \sin e_3 + g(\cdot) + k_2 e_2 + k_2 f_2(\gamma), \end{cases} \tag{12}$$

where $k_1, k_2 \in \boldsymbol{R}$ denote positive, constant, scalar control gains. The scalar function $g(\cdot) \in \boldsymbol{R}$ is defined as follows:

$$g(\cdot)=\frac{\dot{\psi}_t}{2(R-e_1)}\left[(R-e_1-|R_t|)+\left|R-e_1-|R_t|\right|\right], \tag{13}$$

where $R_t=v_t/\omega_t$. In Eq. (12), $f_1(\gamma), f_2(\gamma)\in \boldsymbol{R}$ are all scalar functions. Inspired by the fact that the centrifugal force can be decreased by slowing down the longitudinal velocity and reducing the yaw angle rate, the functions are chosen as

$$f_1(\cdot)=R_{\max}[2\tanh b_1-\tanh(a_1\gamma+b_1)+\tanh(a_1\gamma-b_1)], \tag{14}$$

$$f_2(\cdot)=\theta_{\max}[\tanh(a_2\gamma+b_2)+\tanh(a_2\gamma-b_2)], \tag{15}$$

where $a_1,b_1,a_2,b_2,R_{\max},\theta_{\max}\in \boldsymbol{R}$ are positive constants, and the scalar function $\gamma(t)$ is defined as:

$$\gamma(t)=\frac{v_t^2\sin e_3\cos e_3}{R-e_1}. \tag{16}$$

It should be noted that although the additional feedback terms may result in less effective tracking for the target, the helicopter is guaranteed to fly at a relatively safe manner by this novel design.

Remark 2. The signal of $R_t=v_t/\omega_t$ denotes the turning radius of the target, with $|R_t|\to\infty$ representing straight motion.

Remark 3. From the expression of $R-e_1=\|\boldsymbol{d}\|$, we know that the denominator of the function $g(\cdot)$ will not reach or even approach to zero. Based on this fact and Remark 1, it can be shown that there is no singularity with the controller presented in Eq. (12).

3.3 Stability analysis

In this section, we will analyze the stability of the tracking system under the effect of the proposed controller of Eq. (12).

Theorem 1: Under the control of the proposed controller, both the distance error $e_1(t)$ and the pointing error $e_2(t)$ are bounded, and they are convergent to zero when $|R_t|\to\infty$. Moreover, the trajectory of the helicopter possesses the following property.

Property 1: The helicopter always tracks the target from behind. Namely, during the tracking process, $|e_3(t)|\le \pi/2$. In particular, $e_3(t)\to 0$ as $|R_t|\to\infty$.

Proof: After substituting the control law of Eq. (12) into Eq. (11), we obtained the following closed-loop dynamics:

$$\begin{cases}\dot{e}_1=-k_1e_1-k_1f_1(\gamma),\\ \dot{e}_2=-k_2e_2-k_2f_2(\gamma).\end{cases} \tag{17}$$

In order to illustrate the asymptotic regulation of $e_1(t)$, the following non-negative scalar function $V_1(t)$ is defined:

$$V_1=\frac{1}{2}e_1^2. \tag{18}$$

After taking the time derivative of Eq. (18), then substituting Eq. (17) into the resulting formula, we obtained the following expression for $\dot{V}_1(t)$:

$$\dot{V}_1=-k_1e_1^2-k_1f_1(\gamma)e_1. \tag{19}$$

From Eqs. (14) and (16), we know that the scalar function $f_1(\gamma)$ is bounded by

$$0\leqslant f_1(\gamma)=R_{\max}\big[2\tanh(b_1)-\tanh(a_1\gamma+b_1)+\tanh(a_1\gamma-b_1)\big]\leqslant R_{\max}. \tag{20}$$

After making use of Eq. (20), we obtained the following upper bound for $\dot{V}_1(t)$:

$$\dot{V}_1\leqslant -k_1|e_1|\big[|e_1|-f_1(\gamma)\big]. \tag{21}$$

Clearly, $\dot{V}_1(t)<0$ whenever $|e_1(t)|>f_1(\gamma)$. Therefore, we have

$$\lim_{t\to\infty}|e_1(t)|\leqslant f_1(\gamma). \tag{22}$$

Similarly, we have

$$\lim_{t\to\infty}|e_2(t)|\leqslant f_2(\gamma). \tag{23}$$

Proof for the Property 1: After taking the time derivative of $e_3(t)$ and then substituting Eq. (12) into the resulting expression, we obtained the following formula for $\dot{e}_3(t)$:

$$\dot{e}_3=\dot{\psi}_t-v_t(R-e_1)^{-1}\sin e_3-g(\cdot). \tag{24}$$

In order to illustrate the asymptotic regulation of $e_3(t)$, the following non-negative scalar function $V_3(t)$ is defined:

$$V_3=\frac{1}{2}e_3^2. \tag{25}$$

After taking the time derivative of Eq. (25), substituting Eq. (24) into the resulting expression, we obtained the following upper bound for $\dot{V}_3(t)$:

$$\dot{V}_3=e_3\big[\dot{\psi}_t-v_t(R-e_1)^{-1}\sin e_3-g(\cdot)\big]\leqslant \Gamma(\cdot), \tag{26}$$

where the function $\Gamma(\cdot)$ is defined as

$$\Gamma(\cdot)=\frac{v_t}{\|d\|}|e_3|\big[\chi(\|d\|,R_t)-\sin|e_3|\big], \tag{27}$$

where

$$\chi(\|d\|, R_t) = \frac{(\|d\| + |R_t|) - |(\|d\| - |R_t|)|}{2|R_t|}. \tag{28}$$

Clearly, the function $\chi(\|\boldsymbol{d}\|, R_t)$ possesses the following two properties:

(1) $0 \leqslant \chi(\|\boldsymbol{d}\|, R_t) \leqslant 1$.

(2) $\chi(\|\boldsymbol{d}\|, R_t) = \begin{cases} 1, & \text{when } |R_t| < \|d\|, \\ \dfrac{\|d\|}{|R_t|}, & \text{when } |R_t| \geqslant \|d\|, \\ 0, & \text{when } |R_t| \to \infty. \end{cases}$

Therefore, it is clear that

$$\dot{V}_3 \leqslant \Gamma(\cdot) < 0,$$

whenever

$$|e_3(t)| > \arcsin \chi,$$

therefore, we have

$$\lim_{t\to\infty} |e_3(t)| \leqslant \arcsin \chi < \frac{\pi}{2}. \tag{29}$$

Subsequently, we will prove that the error signal $e_3(t)$ is driven to zero as $|R_t| \to \infty$.

Note that $\chi \to 0$ as $|R_t| \to \infty$, and $\arcsin \chi \to 0$, the inequality (26) can be rewritten as

$$\dot{V}_3 \leqslant -\frac{v_t}{R - e_1} \cdot e_3 \sin e_3. \tag{30}$$

Based on the facts that $v_t(t) > 0$, $e_1(t) < R$ and

$$e_3(t) \sin e_3(t) \geqslant 0, \tag{31}$$

we can conclude that $\dot{V}_3(t)$ is always non-positive. Inequality (30) ensures that the error signal $e_3(t)$ is driven to zero in the sense that

$$\lim_{t\to\infty} e_3(t) = 0. \tag{32}$$

Now, we are ready to prove that the error signals $e_1(t)$ and $e_2(t)$ are convergent to zero as $|R_t(t)| \to \infty$.

Note that $e_3(t) \to 0$ and $\gamma(t) \to 0$ as $|R_t(t)| \to 0$. Hence, we have $f_1(\gamma), f_2(\gamma) \to 0$ from the expressions of $f_1(\cdot)$ and $f_2(\cdot)$. Based on the inequalities (22) and (23), we can easily conclude that

$$\lim_{t\to\infty} |e_1(t)| = 0, \tag{33}$$

$$\lim_{t\to\infty} |e_2(t)| = 0. \tag{34}$$

4 Simulation Results

In this section, computer simulations have been carried out to validate the tracking performance of the proposed method. For the simulation, the initial position of the target and the helicopter are selected as

$$[x_t(t_0), y_t(t_0)]^{\mathrm{T}} = [20, 0]^{\mathrm{T}},$$

$$[x(t_0), y(t_0), z(t_0)]^{\mathrm{T}} = [0, 0, 10]^{\mathrm{T}}.$$

Therefore, the initial distance $\|\boldsymbol{d}(t_0)\| = 20$, which satisfies the Assumption 1. The initial pose of the camera is

$$[\alpha(t_0), \beta(t_0)]^{\mathrm{T}} = [0, \pi/4]^{\mathrm{T}}.$$

The desired horizontal distance is set as

$$R = 10, \ R_{\max} = 5, \ \theta_{\max} = \pi/12.$$

Based on these conditions, two groups of simulation are conducted to test typical cases of the proposed target tracking control system.

In the first group, the target moves along a linear path at a constant speed of $v_t = 5\text{m/s}$, with its orientation as $\psi_t = \pi/4$. The trajectories of the target and the UAV are exhibited in Fig. 5. Fig. 6 indicates the horizontal distance error $e_1(t)$ between the target and the helicopter. Fig. 7 denotes the pointing error $e_2(t)$ and the alignment error $e_3(t)$.

Similar results are obtained in the second simulation, as shown in Fig. 8, Fig. 9 and Fig. 10, respectively. In this group, the target moves along the x-axes with the speed of $v_t = 5\text{m/s}$ firstly, and then takes a sudden turn at $\omega_t = \pi/6(\text{rad/s})$. This specific setting aims to simulate for the maneuvers of the target for the purpose of escaping from tracking.

From the simulation results, it is clear that the horizontal distance $\|\boldsymbol{d}(t)\|$ is convergent to the region $[10, 15]$, and the pointing error $e_2(t)$ is bounded with the boundary of $[-\pi/12, +\pi/12]$. Both the distance error $e_1(t)$ and the pointing error $e_2(t)$ are convergent to zero as the target moves along a linear path. Moreover, both the longitudinal velocity and the yaw angle rate are reduced relatively when the target takes a sudden turn, so that to avoid tracking failure due to evasive maneuvers of the target.

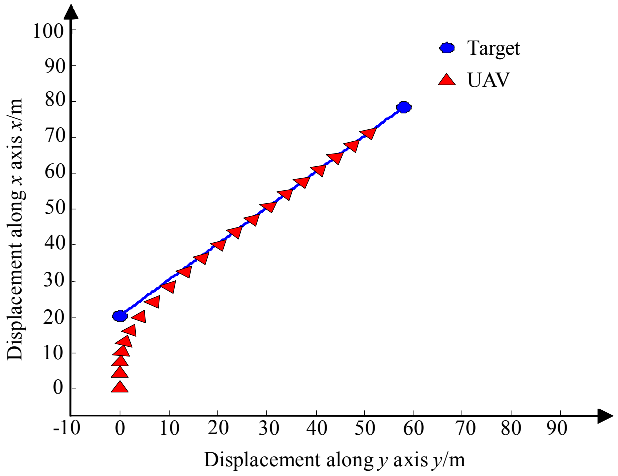

Fig. 5. Tracking performance (Simulation I)

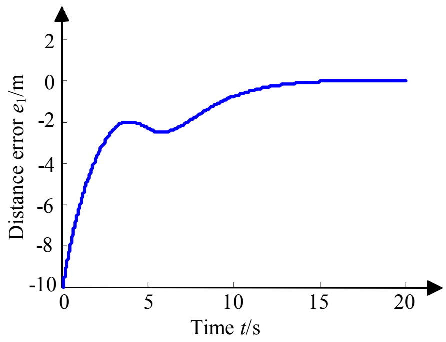

Fig. 6. Distance error $e_1(t)$ (Simulation I)

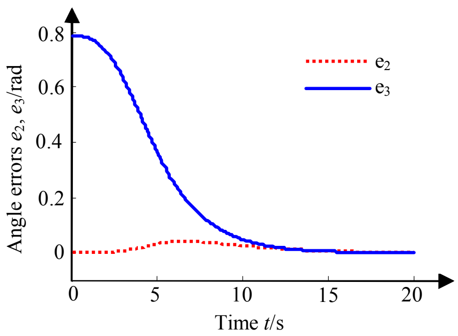

Fig. 7. Angle errors $e_2(t)$ and $e_3(t)$ (Simulation I)

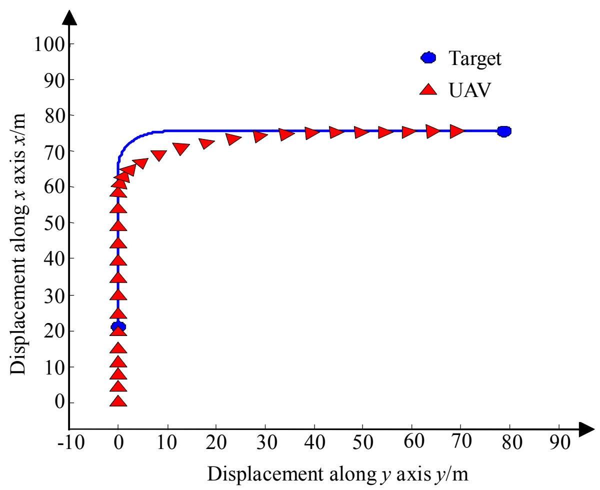

Fig. 8. Tracking performance (Simulation II)

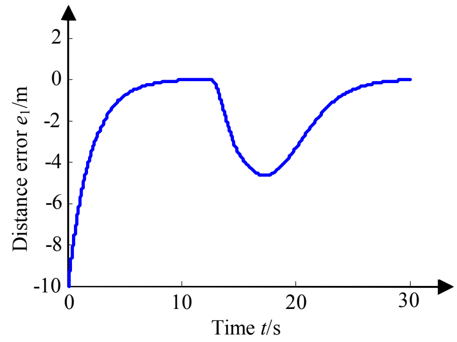

Fig. 9. Distance error $e_1(t)$ (Simulation II)

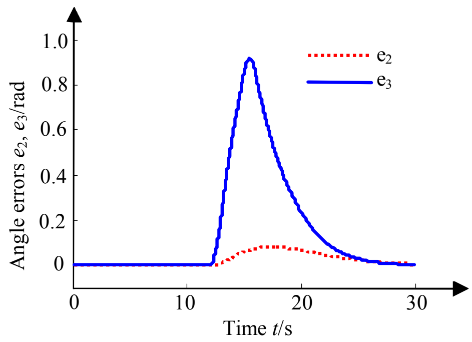

Fig. 10. Angle errors $e_2(t)$ and $e_3(t)$ (Simulation II)

5 Conclusions

(1) To drive an autonomous helicopter to track a ground target, a novel control scheme is proposed, which consists of an innovative target tracking controller and a classical flight controller.

(2) In order to avoid tracking failure due to evasive maneuvers of the target, a novel coordinate transformation is firstly introduced to convert the tracking system into a more compact form convenient for control law design, the desired velocities of the helicopter is then designed with consideration of the dynamic constraint.

(3) A classical control law combined of PID and fuzzy controller is utilized as the flight controller, which drives the helicopter to follow the desired trajectory.

(4) The performance of the proposed method is demonstrated by both theoretical analysis and simulation results.

Future work will focus on various trajectories planning which satisfy tracking objective. Another interest is to utilize other flight controller to further improve the performance of the tracking system.

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