Contents lists available at ScienceDirect
Aerospace Science and Technology
www.elsevier.com/locate/aescte

An active disturbance rejection control guidance law based collision avoidance for unmanned aerial vehicles

Ning Zhang, Wendong Gai *, Guilin Zhang, Jing Zhang

Shandong University of Science and Technology, Qingdao 266590, China

ARTICLE INFO

Article history:
Received 13 December 2017
Received in revised form 25 February 2018
Accepted 30 March 2018
Available online xxxx

Keywords:
Collision avoidance
Collision cone
Active disturbance rejection control
Extended state observer
Circle criterion

ABSTRACT

In this paper, an active disturbance rejection control guidance law is proposed for the problem of unmanned aerial vehicle (UAV) collision avoidance. First, a linear time-varying collision avoidance model based on a collision cone is established. Then the active disturbance rejection control guidance law is designed to ensure the security of UAV collision avoidance. In addition, the stability of a nonlinear active disturbance rejection system with an extended state observer is proved by the circle criterion, and the stability conditions are used to design the guidance coefficients. A simulation system based on a six-degrees-of-freedom UAV model is used to demonstrate the performance of this guidance law. The results conclusively demonstrate that this method can achieve collision avoidance in the presence of sensor noise, an unknown acceleration of an obstacle, and wind disturbance. Moreover, the manoeuvring range of collision avoidance using this method is narrower than the collision avoidance method based on nonlinear dynamic inversion guidance.

1. Introduction

With the rapid development of unmanned aerial vehicles (UAVs) worldwide, their number is increasing significantly. However, safety concerns have restricted the further development and application of UAVs, and UAV collision avoidance has become a formidable challenge.

In the research on the UAV collision avoidance problem, the core idea can be summarized as follows: first, the collision is detected by a specific collision threat detection method, and then an appropriate collision avoidance algorithm is used to drive the UAV to fly away from the hazardous areas [1]. An acceleration command which is the input of the attitude controller for the UAV is generated by a guidance loop.

Collision cone approach is an effective way of collision detection [2]. Closest Point of Approach (CPA) was used for multiple UAVs collision avoidance [3]. To make the collision cone approach more practical for collision avoidance, CPA was widely used in Traffic Alert and Collision Avoidance System (TACAS) [4–6].

In recent years, many researchers have done a lot of research on collision avoidance [7]. An indirect way for UAV collision avoidance is path planning [8,9]. But this also means complex computation for a signal UAV [10]. Proportional navigation (PN) guidance laws have been widely used in missile interception and UAV collision avoidance owing to their simplicity and effectiveness [11,12]. The optimal PN guidance law for UAV collision avoidance was proposed in [13]. However, this guidance law is applicable for a non-manoeuvring obstacle, and its performance may not be guaranteed in case of obstacle acceleration. A nonlinear dynamic inversion (NDI) guidance law is another guidance law widely used in UAV collision avoidance [14–16]. In [17], the use of an NDI guidance law in UAV collision avoidance was reported. Though this law considered the autopilot lag, the disturbance caused by obstacle acceleration was not considered for the UAV collision avoidance. In general, a UAV model is a simplified point-mass model, and disturbances such as unknown obstacle acceleration, sensor noise, or wind disturbance are rarely considered in the existing guidance laws for UAV collision avoidance. In comparison, numerous guidance laws for missile interception have been developed to effectively deal with uncertainty and disturbances, such as the sliding mode guidance law or the guidance law based on disturbance estimation and attenuation [18–21].

Sliding mode control (SMC) plays an important role in missile interception because of its robustness against matched uncertainty [22–25]. [26] reported an adaptive non-singular terminal sliding mode guidance law to intercept a manoeuvring target and an extended state observer (ESO) designed to estimate an unknown disturbance. A lateral guidance law for a UAV based on a high-order sliding mode was presented in [27]. This guidance provided excellent performance in the presence of wind, generating smooth and

* Corresponding author.
E-mail address: gwd2011@sdust.edu.cn (W. Gai).

https://doi.org/10.1016/j.ast.2018.03.048
1270-9638/

graceful manoeuvres, and it reduced the chattering effect while retaining its robustness and accuracy. However, it required high-order derivatives of the switching function.

Disturbance/uncertainty estimation and attenuation techniques are also effective in countering the disturbances and uncertainties [28]. Some methods that are widely applied are a nonlinear disturbance observer (NDOB) [29] and an ESO [30,31]. An NDOB-based three-dimensional guidance law for missile interception was proposed in [32]. The NDOB technique was adopted to estimate constant and time-varying target accelerations. However, the chattering problem was also found to be present because of the combination of the finite-time stability theory and NDOB. In comparison, an ESO does not require any information on the target acceleration, particularly the upper bound information of the time-varying target acceleration. Thus, a new ESO–SMC based finite-time convergent guidance law was proposed in [33], and it could estimate the target acceleration by the ESO. Compared with sliding mode control, ESO requires less information and tremor problems can be effectively reduced. It is to be noted that the guidance laws used for missile interception cannot be used directly for UAV collision avoidance.

In view of the above-mentioned results, a collision avoidance method based on a nonlinear active disturbance rejection control (ADRC) guidance law is proposed in this paper. The main contributions of this paper are summarized as follows:

1) A linear time-varying collision avoidance model is designed according to the collision cone detection.

2) An ADRC guidance law for collision avoidance is developed to deal with disturbances such as the unknown acceleration of the obstacle, sensor noise, and wind disturbance.

3) The stability of the nonlinear ADRC guidance law is proved by the circle criterion, and the stability conditions are used to design the guidance coefficients.

4) A six-degrees of freedom (6-DOF) UAV model is used in the simulation rather than a simplified point-mass model.

The organization of this paper is as follows. Section 2 is devoted to the collision detection approach, and the collision avoidance model is proposed in it. In Section 3, the ADRC guidance law is presented, and the stability of the nonlinear ADRC system is proved. Section 4 discusses the results of the numerical simulations performed with MATLAB. Finally, some conclusions and remarks are given in Section 5.

2. Model of collision avoidance

For collision avoidance, it is important to use a collision detection approach which can predict any possible collision with an obstacle and compute an alternate aiming direction for the UAV to avoid the obstacle. The geometric configuration of the collision cone is illustrated in Fig. 1.

As shown in Fig. 1, the collision cone is defined by four points denoted as A, B, C, and D. In the figure, A and C are the locations of the UAV and obstacle, respectively, B and D are the aiming points of collision avoidance, V is the velocity of the UAV, V_{ob} is the velocity of the obstacle, ψ and ψ_{ob} are the heading angles of the UAV and obstacle, λ the line of sight (LOS) angle, γ is the angle between the boundary of the collision cone and LOS, and ε is the angle between the relative velocity vector and LOS.

The condition of collision avoidance achievement is that relative velocity vector $\vec{V}_{rel}$ aligns with the boundary of the collision cone in a finite time. Thus, the collision avoidance progress is the tracking of collision cone boundary angle μ by angle of relative velocity ψ_{rel}.

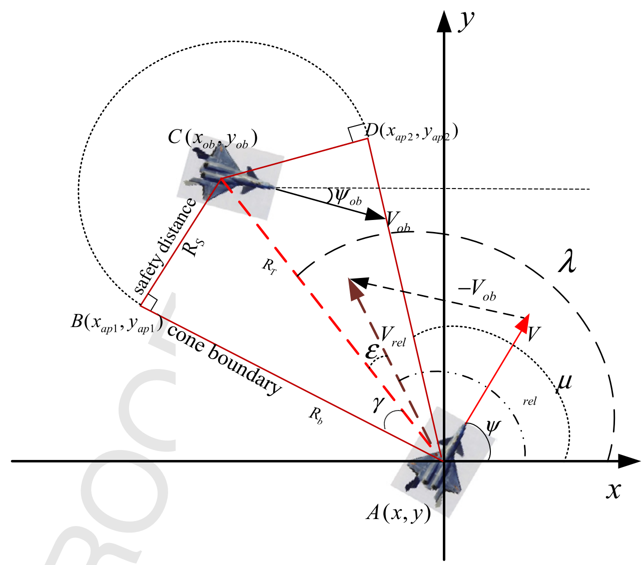

Fig. 1. Geometric configuration of the collision cone.

Relative velocity $\vec{V}_{rel}$ can be obtained by

$$\begin{aligned}\vec{V}_{rel} &= \vec{V} - \vec{V}_{obs} \\ &= V\cos(\psi_{rel} - \psi) + V_{obs}\cos(\pi + \psi_{obs} - \psi_{rel})\end{aligned} \tag{1}$$

where $\vec{V}$ is the velocity vector of UAV and $\vec{V}_{obs}$ is the velocity vector of obstacle.

Safety distance R_S is the distance that guarantees the safety of the UAV. It is a constant determined by the designer.

The UAV will collide with the obstacle if Eq. (2) is satisfied. Then it will switch to the path of collision avoidance.

$$|\lambda - \psi_{rel}| = \varepsilon < \gamma \tag{2}$$

where

$$\psi_{rel} = \pi + \tan^{-1}\left(\frac{V\sin\psi + V_{ob}\sin(\pi + \psi_{ob})}{V\cos\psi + V_{ob}\cos(\pi + \psi_{ob})}\right), \tag{3}$$

$$\lambda = \pi + \tan^{-1}\left(\frac{y - y_{ob}}{x - x_{ob}}\right). \tag{4}$$

The UAV has two collision avoidance strategies when the collision may occur: one is to avoid the collision along the cone boundary *AD*; another is to avoid the collision along the cone boundary *AB*. The UAV should avoid collision in the opposite direction of obstacle's flight if it is less than $\pi/2$, otherwise, the UAV should avoid collision along the direction of the obstacle's flight if it is greater than $\pi/2$. Therefore, the direction of the guidance command can be determined by

$$\begin{cases} a(t) > 0 & \dfrac{\pi}{2} \le |\psi_0 - \psi_{\mathrm{OB}}| < \pi \\ a(t) < 0 & 0 < |\psi_0 - \psi_{\mathrm{OB}}| < \dfrac{\pi}{2} \end{cases} \tag{5}$$

$\vec{V}_{rel}$ tracks collision cone boundary *AD* or *AB* in finite time according to Eq. (5). The UAV enters the normal flight mode to track the target point when the collision avoidance is completed.

The model of collision avoidance can now be described as follows.

First, according to Fig. 1 and UAV dynamic model, the following equation can be derived.

Please cite this article in press as: N. Zhang et al., An active disturbance rejection control guidance law based collision avoidance for unmanned aerial vehicles, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.03.048