The Intelligent Flight Control of Quadrotor in Tunnel Based on Simple Sensors

Rui Li and Yingjing Shi

Abstract This paper studies the automation flight control problem of a quadrotor in the tunnel. The LED lamp belt is installed in the tunnel and two moving points are the tracking target of the quadrotor. The velocity-control-mode is first well done before the tracking control algorithm is considered. A control law is then designed to achieve tracking task in the straight tunnel. When the parameter is properly designed, the quadrotor still can perform tracking task for the moving points even in the bent tunnel. Moreover, we prove that the collision between the quadrotor and the tunnel can be avoided by using the proposed control law. The validity of the proposed control algorithm is also demonstrated through numerical simulations.

Keywords Quadrotor · Automation flight · Tracking · Collision avoidance

1 Introduction

With the potential, both in military and civilian applications, for reconnaissance, surveillance, disaster management and emergency aid, unmanned aerial vehicles (UAVs) have gained great interesting among the research community. An important subset of UAVs is quadrotors, which have become popular recently due to their small size and maneuverability.

The development of quadrotor navigation and control technologies in indoor or enclosed environments has been an active area of research. Thomas et al. [1] developed a nonlinear vision-based controller for trajectory tracking in the image space, which made a step towards enabling grasping maneuvers using vision. In [2], the authors proposed a stochastic differential equation-based exploration algorithm

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Y. Jia et al. (eds.), *Proceedings of 2017 Chinese Intelligent Systems Conference*, Lecture Notes in Electrical Engineering 460,
https://doi.org/10.1007/978-981-10-6499-9_2

to enable exploration in three-dimensional indoor environments with a payload constrained micro-aerial vehicle. Budiyono et al. [3] presented control system and collision detection system design for a quadrotor using a Kinect sensor. There is other work on control or navigation system design based on the indoor localization system. Examples include: balancing a pendulum [4]; aggressive maneuvers, such as flight through windows [5] or flips [6]; ball juggling with a racket [7] and so on. However, the indoor localization system is usually expensive and does not suit for narrow and dark environment.

Recently, the automation flight control of the quadrotor in tunnel has attracted much attention due to the important applications including exploration, surveillance, rescue, etc. However, the automation flight control of the quadrotor in the tunnel is difficult due to the limited space, dark environment, weak signal, etc. So far, the study on the automation flight control of the quadrotor in the tunnel environment is still in the early stage.

In this paper, we take a step to investigate the navigation and control problem of the quadrotor in the tunnel. Since the automation flight with known environment is a critical step for fully automation, we carry out the investigation on how to perform the automation flight in the known environment, where LED lamp belt is installed in the tunnel to simulate a known environment. The control system is designed to track two moving points on LED lamp belt in the tunnel, which can be viewed as a coordination problem of the multi-agent system and is solved by using the coordination control method.

The study on coordination control of multi-agent systems, based on a distributed control scheme, has received a great deal of attention and has interested many researchers due to their widespread applications in various real-world multi-agent systems. In the area of cooperative control of multi-agent systems, tracking is an important and fundamental problem, which has been extensively investigated. The authors in [8] and [9] proposed and analyzed a consensus tracking algorithm under a variable undirected network topology. In [10] and [11], the authors proposed a proportional-and-derivative-like consensus tracking algorithm under a directed network topology in both continuous-time and discrete-time settings. In [12], the authors studied a leader-follower consensus tracking problem with time-varying delays. In [13], the author studied a flocking algorithm under the assumption that the leader's velocity is constant and is available to all followers. In [14], the authors studied the problem of flight formation and trajectory tracking control for a group of mini rotorcraft. Schoellig et al. [15] presented an optimization-based iterative learning approach for trajectory tracking and the approach was successfully applied to quadrotor vehicles.

In this paper, we first describe the tracking problem of the quadrotor. Then we show the velocity controller design for the quadrotor. Base on the velocity controller, we establish the control algorithm, achieving the tracking task for the LED lamp either in the straight part of the tunnel or the curve part of the tunnel.

2 Problem Formulation

IMU has been the standard configuration for the intelligent aircraft and the main tasks of the intelligent aircraft are early-warning and reconnaissance, which are usually achieved with the help of the camera. Thus, this paper considers the problem of control system design for the quadrotor equipping with IMU and camera to achieve intelligent flight in the tunnel.

Suppose that there is no curve in the vertical section of the tunnel, and the LED lamp belt is installed in the tunnel, where $\boldsymbol{r}_1$, $\boldsymbol{r}_2$ are two moving points on the LED lamp belt and the velocity of $\boldsymbol{r}_1$, $\boldsymbol{r}_2$ is constant and known. We aim to design the control system by which the quadrotor flights keeping the same height and certain distant with the lamp belt. Suppose that the quadrotor looks at the two points $\boldsymbol{r}_1$, $\boldsymbol{r}_2$ simultaneously, $r = r_2 - r_1$, $\bar{r} = (r_1 + r_2)/2$, and $\hat{r}$ is the adjoint point of $\bar{r}$, satisfying

$$\hat{r} = \begin{cases} \bar{r} + d\frac{r \times z}{\|r \times z\|}, & \|r \times z\| \neq 0, \\ \bar{r} + d\frac{(r \times z)^-}{\|(r \times z)^-\|}, & \|r \times z\| = 0. \end{cases} \tag{1}$$

Here, $z = [0 \quad 0 \quad 1]^{\mathrm{T}}$; $(r \times z)^-$ is the left limit of $r \times z$ when the quadrotor enters the vertical tunnel.

Remark 1 Since there is no curve in the vertical segment of the tunnel, that is, $(r \times z)/\|r \times z\|$ is same when the quadrotor just enters the vertical segment and just departs from the vertical segment.

3 Velocity Controller Design

In order to perform tracking task for moving points in the tunnel, we first need to achieve the velocity control of the quadrotor. In this paper, the PID algorithm is applied to design the velocity controller of the quadrotor.

Based on the well-done attitude control, we solve the expected flight velocity via PID algorithm to obtain the anticipant axial acceleration. Then, we transform the acceleration to body axis system by using rotation matrix conversion, which is the control input. The transform relationship is given as follows.

$$\begin{cases} \theta_{des} = \arctan\left(\dfrac{a_x}{a_z}\right) \\ \phi_{des} = -\arctan\left(\dfrac{a_y \cos(\theta)}{a_z}\right) \end{cases}$$

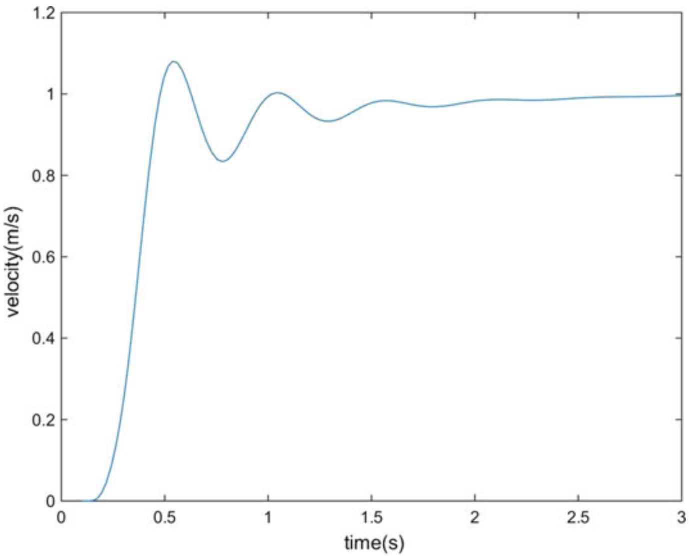

Fig. 1 Simulation result of the velocity controller

Here, $(\theta_{des}, \phi_{des})^T$ stands for the expected value of the pitching angle and rolling angle, $(a_x, a_y, a_z)^T$ is the value of the acceleration when the earth coordinate system is converted to the temporary coordinate system (the temporary coordinate system has the same heading angle with the body axes coordinate system, but pitching angle and rolling angle under the temporary coordinate system are zero). The simulation result of the velocity controller is given below.

From Fig. 1 we can find that the quadrotor can tack the expected velocity fast and stably. Thus it can be used for the design of the control algorithm to achieve tracking of the adjoint point.

4 Tracking Control

When achieving velocity control for quadrotor, we introduce the following control law to perform tracking task for the moving points:

$$\dot{x} = v\frac{r}{\|r\|} + K_v(\hat{r} - x) \tag{2}$$

Here, x is the position of the quadrotor; v, r, $\hat{r}$ are given as mentioned earlier; K_v is larger than zero, which is an unknown value to be determined. In order to avoid collision with the tunnel, K_v is usually selected according to the velocity v of LED lamp, the distance d between adjoint point and lamp belt, and the curvature of the tunnel.

4.1 The Theoretical Analysis of the Tracking Problem

Theorem 1 *For the straight part of the tunnel, when the control method given by Eq. (2) is applied, the quadrotor can achieve accurate tracking for the adjoint point.*

Proof For the straight tunnel, considering Eq. (1), we have

$$\dot{\hat{r}} = \frac{\dot{r}_1 + \dot{r}_2}{2} = v\frac{r}{\|r\|}.$$

Thus, it can be seen from Eq. (2) that

$$\dot{x} - \dot{\hat{r}} = -K_v(x - \hat{r}).$$

Let $e = x - \hat{r}$. We have $\dot{e} = -K_v e$, $K_v > 0$. Obviously, the error between the quadrotor and the adjoint is exponentially convergent.

Theorem 2 Suppose that the curvature radius of the tunnel is ρ, the moving velocity of the LED lamp belt is v, and the distance between the adjoint point and the LED lamp belt is d. Then, the quadrotor is able to keep the flight distance with the adjoint point not more than d when we choose $K_v \geq vd/\rho l$.

Proof Since the maximal deviation between the velocity of adjoint point and the velocity of LED lamp occurs in the horizontal tunnel, thus we have

$$\dot{\hat{r}} = v\frac{\rho \pm d}{\rho}\frac{r}{\|r\|}, \tag{3}$$

where $\pm$ denotes that $\pm(\bar{r} - \hat{r})$ points the center of the turning circle. From Eq. (2), we have

$$\dot{x} = v\left(1 \pm \frac{d}{\rho} \mp \frac{d}{\rho}\right)\frac{r}{\|r\|} + K_v(\hat{r} - x).$$

Substituting Eq. (3) into the above equation, we obtain that

$$\dot{x} - \dot{\hat{r}} = \mp\frac{vd}{\rho}\frac{r}{\|r\|} + K_v(\hat{r} - x).$$

Let $e = x - \hat{r}$, we get

$$\dot{e} = \mp \frac{vd}{\rho} \frac{r}{\|r\|} - K_v e.$$

Therefore, the quadrotor can keep the flight distance with adjoint point not more than l, only if

$$\|K_v e\| \geq \left\| \frac{vd}{\rho} \frac{r}{\|r\|} \right\|,$$

when $\|e\| \geq l$, that is, $K_v \geq vd/\rho l$.

Theorem 3 *Suppose that the distance between the initial position of the quadrotor and the adjoint point is less than d. If the control method given by Eq.* (2) *is applied, the collision between the quadrotor and the tunnel can be avoided.*

Proof We only need to illustrate that under the assumption of the theorem, with the control method given by Eq. (2), the quadrotor can avoid collision with the tunnel either for the straight tunnel or curved tunnel.

In the straight tunnel, the distance between the quadrotor and the adjoint point is exponentially convergent, thus the theorem is clearly established. For the curved tunnel, if let $l = d$ in Theorem 2, it can be easily obtained that the quadrotor can keep the flight distance not more than d from the adjoint point, that is, $K_v \geq v/\rho$. Thus, the quadrotor can avoid collision with the tunnel.

4.2 Simulation

The simulation is carried out in Matlab environment, where fixed-step simulation is applied and ODE solver applies fourth-order Runge-Kutta method.

The first simulation considers the situation in the spiraling tunnel. The curvature radius of the tunnel is 3 m, the velocity of the LED lamp is 1 m/s, the distance between the adjoint point and the LED lamp belt is 0.5 m, and the distance between two LED lamps is 0.5 m. The initial position of the LED lamp is set at origin, the initial position coordinate of the quadrotor is $[-1 \quad -1 \quad 0.5]^{\mathrm{T}}$, and K_v is set to be 2.

The simulation result is shown in Fig. 2, where the blue line stands for the trajectory of the LED lamp, the green line stands for the trajectory of the adjoint point, the red line stands for the trajectory of the quadrotor, the hollow circle stands for the starting position of the simulation, and solid circle stands for the stopping position of the simulation. It can be seen from the simulation that, the quadrotor can track the adjoint point perfectly, which indicates that the quadrotor can safely flight in the tunnel.

The second simulation considers the situation in the vertical tunnel. The first part of the tunnel is an arc-shaped climbing course with the curvature radius as 3 m and

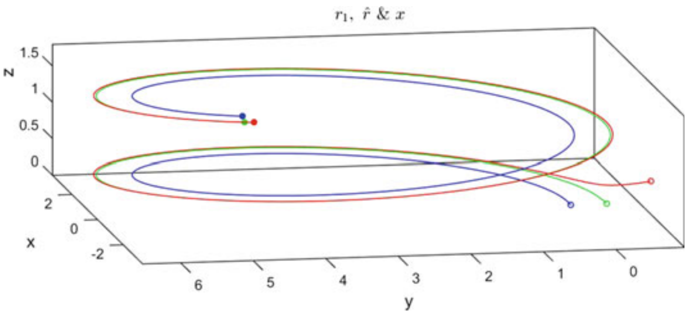

Fig. 2 The simulation curve of the spiraling tunnel

the arc length as 3 m, and the subsequent part is the straight tunnel being tangent to the circular arc. The data of the LED and the quadrotor are as same as what given in the above simulation, and $K_v = 1$ (Fig. 3).

From the simulation result, we can find that the quadrotor can track the adjoint point with the complicated environment. Since the tracking error between the quadrotor and adjoint point is exponentially convergent, then the quadrotor can well track the adjoint point in the straight part. It can be seen from the simulation that, the quadrotor can safely flight in the tunnel.

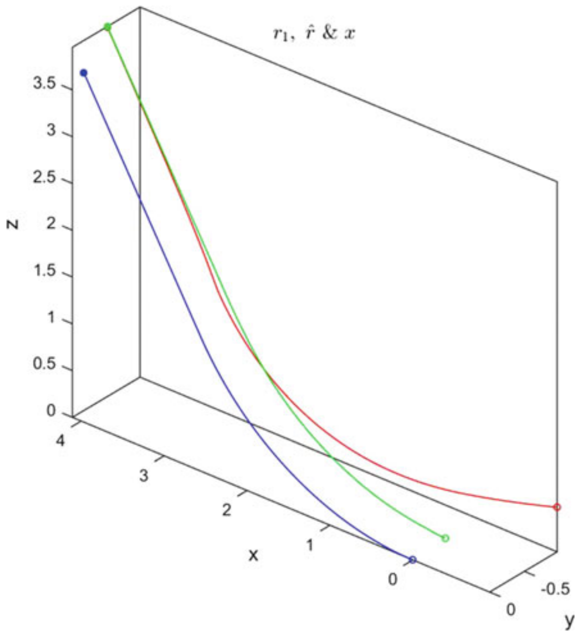

Fig. 3 The simulation of the vertical tunnel

5 Conclusions

We have proposed an algorithm for tracking the moving target in the tunnel by a quadrotor equipping with IMU and camera. The proposed control algorithm can track the moving point in the straight tunnel or bent tunnel, and the collision avoidance can be achieved by the control algorithm. The paper is the first step to investigate the automation flight control of the quadrotor in the tunnel environment. The quadrotor can achieve the automation flight for the known environment by the proposed control method, which can be used to construct fully automation control algorithm. The future work includes the application of the algorithm on the real quadrotor plat and the fully automation flight control algorithm design in tunnel.

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http://www.springer.com/978-981-10-6498-2

Proceedings of 2017 Chinese Intelligent Systems Conference
Volume II
Jia, Y.; Du, J.; Zhang, W. (Eds.)
2018, XI, 787 p. 367 illus., Hardcover
ISBN: 978-981-10-6498-2