Tracking control of quadrotors in the presence of obstacles based on potential field method

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ABSTRACT

In this paper, by introducing a robust hybrid controller using an obstacle avoidance unit based on potential functions, the trajectory tracking control of quadrotors in the presence of obstacles is discussed. Quadrotors are underactuated systems and the design of a robust tracking controller has become one of the most challenging topics in recent researches. First, dynamic modeling of a quadrotor is considered using the Newton-Euler method by considering the nonlinear terms. In the following, the system state space is represented. Then, a control method based on linear control algorithms is designed to control the outer loop and for the inner loop of the controller, the backstepping method is presented. The combination of the control methods is designed to obtain the best performance of the system in terms of convergence to the reference path, minimum steady-state errors and transient response specifications of the system. In the following, an obstacle avoidance unit based on potential functions is designed to prevent the collision of the quadrotor with obstacles by creating a repulsive force between the system and the obstacles. Finally, trajectory tracking case studies are considered for a quadrotor in the presence of obstacles. Obtained results show the robust performance of the controller in tracking the trajectories and avoiding obstacles.

KEYWORDS

Quadrotor, backstepping control method, obstacle avoidance unit, potential function, trajectory tracking control.

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1. Introduction

Control of quadrotors has become one of the most important topics in research and they are widely used in various industries and applications [1].

Researchers first studied the dynamic modeling of quadrotors, then they considered the effect of aerodynamic forces [2]. Adaptive control [3], feedback linearization [4] and backstepping [5] are some of the methods used to control quadrotors. The basic benefits of the backstepping method are step by step design process and the stability of the closed-loop system simultaneously. This method is simply combined with other control methods, such as maximum convergence to the reference path by testing the possible combinations thus the designer can achieve the best possible control algorithm. Therefore, this method can be combined with a method that protects the quadrotor against obstacles. In [6], a robot is controlled in the presence of obstacles based on Lyapunov functions. For the first time in [7] a control algorithm based on potential functions is proposed for the system in an obstacle-rich environment. In [8], an autonomous underwater vehicle was controlled using potential functions in the presence of obstacles.

In this study, the backstepping method is combined with linear control algorithms and an obstacle avoidance unit based on potential functions to reach minimal steady-state errors and excellent convergence to the reference path in the presence of multiple obstacles in complex maneuvers.

2. Methodology

At the beginning of the modeling, two Cartesian coordinates are specified for the system. One is the inertia frame, which has fixed orientations, and the other is a body frame attached to the system. Figure 1 shows the locations of the quadrotor and Cartesian coordinates.

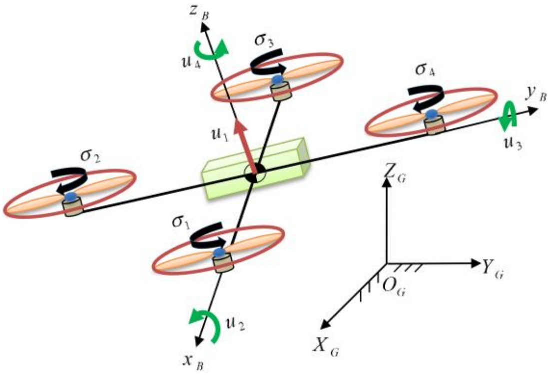

Figure 1. Quadrotor coordinate system shematic diagram

In this figure, $O_G X_G Y_G Z_G$ is the inertia frame and $o_B x_B y_B z_B$ is body frame. $(\sigma_1, \sigma_2, \sigma_3, \sigma_4)$ are angular velocities of the propellers and (u_1, u_2, u_3, u_4) are the control inputs. These parameters relate to each other with matrice A as follows:

$$[u_i]_{4\times1} = A\left[\sigma_i^2\right]_{4\times1} \tag{1}$$

$$A = \begin{bmatrix} b & b & b & b \\ 0 & -bl & 0 & bl \\ -bl & 0 & bl & 0 \\ -d & d & -d & d \end{bmatrix} \tag{2}$$

where b, d and l are the thrust coefficient, the drag coefficient and the distance between the center of each rotor and geometric center of the quadrotor, respectively.

Dynamic modeling of quadrotors has been done using the Newton-Euler formulation considering all nonlinear parameters in many references such as [9], as follows:

$$\begin{aligned}
\ddot{x} &= (\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi)\frac{u_1}{m} - \frac{\gamma_x}{m}\dot{x} \\
\ddot{y} &= (\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi)\frac{u_1}{m} - \frac{\gamma_y}{m}\dot{y} \\
\ddot{z} &= (\cos\phi \cos\theta)\frac{u_1}{m} - g - \frac{\gamma_z}{m}\dot{z} \\
\ddot{\phi} &= \dot{\theta}\dot{\psi}\frac{(I_y - I_z)}{I_x} - \frac{J_r}{I_x}\dot{\theta}\sigma + \frac{u_2}{I_x} - \frac{\gamma_\phi}{I_x}\dot{\phi}^2 \\
\ddot{\theta} &= \dot{\phi}\dot{\psi}\frac{(I_z - I_x)}{I_y} + \frac{J_r}{I_y}\dot{\phi}\sigma + \frac{u_3}{I_y} - \frac{\gamma_\theta}{I_y}\dot{\theta}^2 \\
\ddot{\psi} &= \dot{\phi}\dot{\theta}\frac{(I_x - I_y)}{I_z} + \frac{u_4}{I_z} - \frac{\gamma_\psi}{I_z}\dot{\psi}^2
\end{aligned} \tag{3}$$

where $(x, y, z, \phi, \theta, \psi)$ are quadrotor position and orientation parameters, (I_x, I_y, I_z, J_r) are moments of inertia, m is mass of the quadrotor, g is gravity acceleration, $(\gamma_x, \gamma_y, \gamma_z, \gamma_\phi, \gamma_\theta, \gamma_\psi)$ are aerodynamic friction coefficients and $\sigma = \sigma_2 + \sigma_4 - \sigma_1 - \sigma_3$.

Figure 2 indicates the proposed closed-loop control diagram for a quadrotor to track the trajectories in the presence of obstacles.

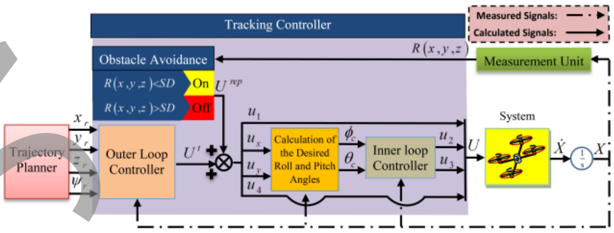

Figure 2. Control diagram

Measurement unit calculates the distance between the quadrotor and any obstacle at any moment. If the distance is less than the considered safe distance, the obstacle avoidance unit is activated and provides the inputs needed to prevent the quadrotor from colliding with the obstacles.

3. Results and Discussion

To evaluate the performance of the proposed controller, two different maneuvers were analyzed using MATLAB software. Figure 3 demonstrates the first maneuver in which the quadrotor successfully tracks the circular path and bypasses the obstacle.

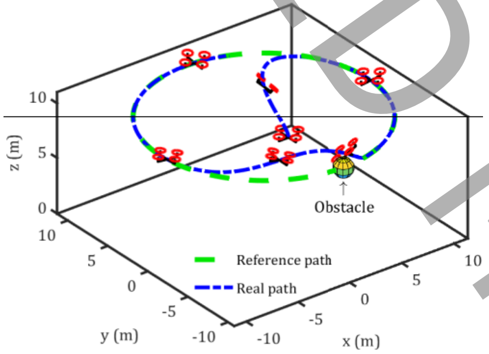

Figure 3. Tracking the circular trajectory with an obstacle

Figure 4 shows the second experiment in which the quadrotor successfully tracks the hyperbolic paraboloid type reference trajectory with multiple obstacles.

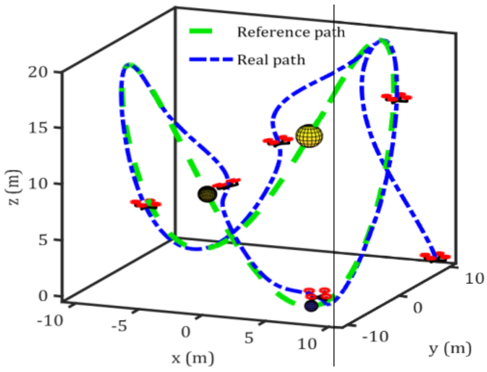

Figure 4. Tracking complex trajectory with multiple obstacles

4. Conclusion

In this paper, using a control strategy based on potential functions, the quadrotor successfully tracks the desired paths without encountering obstacles. When the quadrotor enters an unsafe area (near obstacles), the controller activates the obstacle avoidance unit and using potential functions, provides the virtual deterrent force to avoid obstacles. The combination of control methods was designed to obtain the best performance in terms of steady-state errors and transient response specifications.

5. References

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