LEADER-FOLLOWER FORMATION CONTROL OF QUADROTORS WITH COLLISION AVOIDANCE USING ARTIFICIAL POTENTIAL FIELD

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Abstract

This paper presents a collision-free virtual leader-follower formation control for a group of quadrotors using artificial potential field (APF) and proportional--derivative (PD) controller. The proposed control approach consists of PD controllers that stabilise the attitude, as well as for the position control. To avoid collision with obstacles, APF algorithm is used at the outer-most loop whereby the collision-free path is fed into the position control. Several simulation experiments were carried out to validate the proposed approach. Results show that the integration of APF to the controller were able to avoid obstacles.

Keywords: Formation control, multi-agent system, leader-follower, artificial potential field, unmanned aerial vehicle

INTRODUCTION

The versatility and utility of the unmanned aerial vehicle (UAV) in many sectors such as e-commerce, energy, transportation, and civil for applications like as delivery, inspection, and monitoring has attracted a lot of interest in recent decades. The quadrotor, which has a simple structure and the capacity to take off and land vertically, is among the most popular varieties of UAV (Noordin et al. 2021). Formation of multiple quadrotors is thought to provide more benefits in terms of redundancy, reconfiguration ability, and structural flexibility as compared to the single quadrotor.

Different formation control approaches have been proposed by researchers over the years. Some of the most popular methods are virtual-structure (Ren and Beard 2003), leader-follower (Vallejo-Alarcón, Castro-Linares, and Velasco-Villa 2015), and consensus-based approach (Lazim et al. 2019). Virtual Structure (VS) is a method that initialize each present unmanned vehicle in a formation in its own place according to the formation shape. The vehicles maintained their spot relative to each other in a rigid way. The consensus-based formation approach utilizes graph theory to define the interactions between quadrotors (Lazim et al. 2017). On the other hand, leader-follower formation is made up of one leader and the rest as followers. The biggest advantage of leader-follower method is its simplicity. Here, the appointed leader in the formation moves in a predefined trajectory while the followers track the leader's trajectory. It simply requires two controllers, one for the leader and another one for each follower in the formation (Mat Lazim et al. 2021).

For a group of quadrotors that are flying in leader-follower formation, collision avoidance is one of the main issues that needs to be considered. Artificial potential field (APF) is aa collision avoidance method which was first proposed by Khatib (1985) for manipulators and mobile robots. Robot collision avoidance has previously been studied as a component of higher levels of control in hierarchical robot control systems. It has been approached as a planning problem, with research focusing on the development of a collision-free patch planning method. In this paper, we propose APF to provide a collision-free path for a group of quadrotors that are flying in formation using leader-follower approach with PD controller as attitude and position controller.

The paper is organized as follows. In section 2, mathematical model for a quadrotor is presented, followed by the attitude and position control using PD controller. Leader-follower formation control is described in section 3. Then, APF implementation is presented in section 4, followed by simulation results and discussion in section 5. Lastly, conclusion of the work is given in section 6.

METHODOLOGY

Quadrotor Dynamics

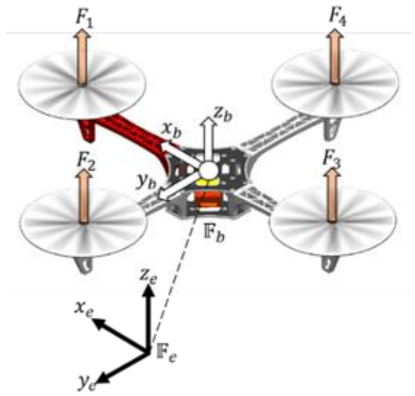

Figure 5 Quadrotor configuration

Consider the quadrotor dynamics shown in Figure 5 as follows (Mahmood and Kim 2015):

$$\ddot{x} = \big(c(\phi)s(\theta)c(\psi) + s(\phi)s(\psi)\big)\, u_1/m \tag{1}$$

$$\ddot{y} = \left(c(\phi)s(\theta)s(\psi) - s(\phi)c(\psi)\right) u_1/m \quad (2)$$

$$\ddot{z} = -a_g + \left(c(\phi)c(\theta)\right) u_1/m \quad (3)$$

$$\ddot{\phi} = \dot{\theta}\dot{\psi}\left(I_{yy} - I_{zz}\right)/I_{xx} + u_2/I_{xx} \quad (4)$$

$$\ddot{\theta} = \dot{\phi}\dot{\psi}\,(I_{zz} - I_{xx})/I_{yy} + u_3/I_{yy} \quad (5)$$

$$\ddot{\psi} = \dot{\phi}\dot{\theta}\left(I_{xx} - I_{yy}\right)/I_{zz} + u_4/I_{zz} \quad (6)$$

with the terms $s(\cdot)$ and $c(\cdot)$ represent the sine and cosine functions, respectively. The position of the quadrotor w.r.t. the earth frame is denoted by (x, y, z), while the attitude is described by Euler angles (ϕ, θ, ψ). Meanwhile, u_k $(k = 1, \ldots, 4)$ are the four control inputs, m is the quadrotor mass, a_g is the gravitational acceleration, I_{pp} $(p = x, y, z)$ denote the moment of inertia along each axis.

Attitude and Position Control

Proportional-derivative controller can be derived for the attitude control of quadrotor. With the system operating in hover state, simple PD controller is given as follows:

$$u_1 = \frac{-m}{c(\phi)c(\theta)}\left(-g + k_{p,z}(z^d - z) + k_{d,z}(\dot{z}^d - \dot{z})\right) \quad (7)$$

$$u_2 = k_{p,\phi}(\phi^d - \phi) + k_{d,\phi}(\dot{\phi}^d - \dot{\phi}) \quad (8)$$

$$u_3 = k_{p,\theta}(\theta^d - \theta) + k_{d,\theta}(\dot{\theta}^d - \dot{\theta}) \quad (9)$$

$$u_4 = k_{p,\psi}(\psi^d - \psi) + k_{d,\psi}(\dot{\psi}^d - \dot{\psi}) \quad (10)$$

Here, $k_{p,z}, k_{p,\phi}, k_{p,\theta}, k_{p,\theta}$ are the proportional gains, while $k_{d,z}, k_{d,\phi}, k_{d,\theta}, k_{d,\psi}$ are the derivative gains. Meanwhile, superscript d represents the desired value of the parameters. These values are obtained from the position control given as follows:

$$\phi^d = k_{p,y}\left(y_b^d - y_b\right) + k_{d,y}\left(\dot{y}_b^d - y_b\right) \quad (11)$$

$$\theta^d = k_{p,x}\left(x_b^d - x_b\right) + k_{d,x}\left(\dot{x}_b^d - x_b\right) \quad (12)$$

where $k_{p,y}, k_{p,x}$ are the proportional gains, and $k_{d,y}, k_{d,x}$ are the derivate gains. Symbol x_b^d and y_b^d are the desired x and y positions w.r.t. body frame, respectively. Also, x_b and y_b are the quadrotor's x and y positions w.r.t. body frame, respectively. The quadrotor's position w.r.t. body frame (x_b^d, y_b^d, x_b, y_b) is obtained from global frame (x^d, y^d, x, y) through the following equations:

$$x_b = x.c(\psi) + y.s(\psi) \quad (13)$$

$$y_b = x.s(\psi) + y.c(\psi) \quad (14)$$

$$x_b^d = x^d . c(\psi) + y^d . s(\psi) \tag{15}$$

$$y_b^d = x^d . s(\psi) + y^d . c(\psi) \tag{16}$$

where x^d and y^d are the desired x and y position of the quadrotor, respectively.

Artificial Potential Field

In this study, each quadrotor is equipped with APF at the outer loop control for avoiding collision. APF turns the place settings into potential field where objective points possess attractive field while obstacles are surrounded with repulsive field. In addition to that, repulsive and attractive forces are also applied within the drone formation to maintain the formation. APF method's main advantage is its capability of avoiding obstacles when implemented. This approach has been implemented across a wide array of mobile robots, AUV, boats, humanoid robots and rovers [10]. Artificial potential field is a sum of attractive potential force $Fatt$ and the repulsive force $Frep$ given as follows:

$$FAPF = Fatt + Frep \tag{17}$$

The APF used in this method evaluates the best next point using a cost function. The cost function can be written as,

$$J = J_{obs} + J_T \tag{18}$$

where J_{obs} is the repulsive potential from the obstacles while the J_T is the attractive potential from that is emitted by the goal. The potential functions of each respective force are:

$$J_{obs} = a_o e^{-\mu_o((x-x_o)^2+(y-y_o)^2)} \tag{19}$$

$$J_T = -a_o e^{-\mu_o((x-x_T)^2+(y-y_T)^2)} \tag{20}$$

where a_o and a_T are the height or depth of the repellent or attractant, respectively which set to 1. Meanwhile μ_o and μ_T are the repellent or attractant's width, respectively which set to 4.

In this proposed method, Artificial Points (AP) are constantly generated around the quadrotor. The number of AP determines the quadrotor's step size. The higher number of AP will result in smaller step size which means higher accuracy. AP is created as a way for the quadrotor to choose the best next step/coordinate to go to. The quadrotor moves from its initial point in a straight line towards the goal until the sensor detects an obstacle. Then, the best AP is chosen based on the following criteria:

$$\text{Distance error} = e_s^d(t + dt) = d_s(t + dt) - d_s(t) < 0$$

$$\text{Potential error} = e_s^J(t + dt) = J(\theta(t + dt)) - J(\theta(t)) < 0$$

$t + dt$ is the artificial particles, t is the quadrotor's current position and $d_s(t + dt)$ is the distance from the artificial point to the target. The best AP criteria is when its distance error and potential error is the smallest in value or negative.

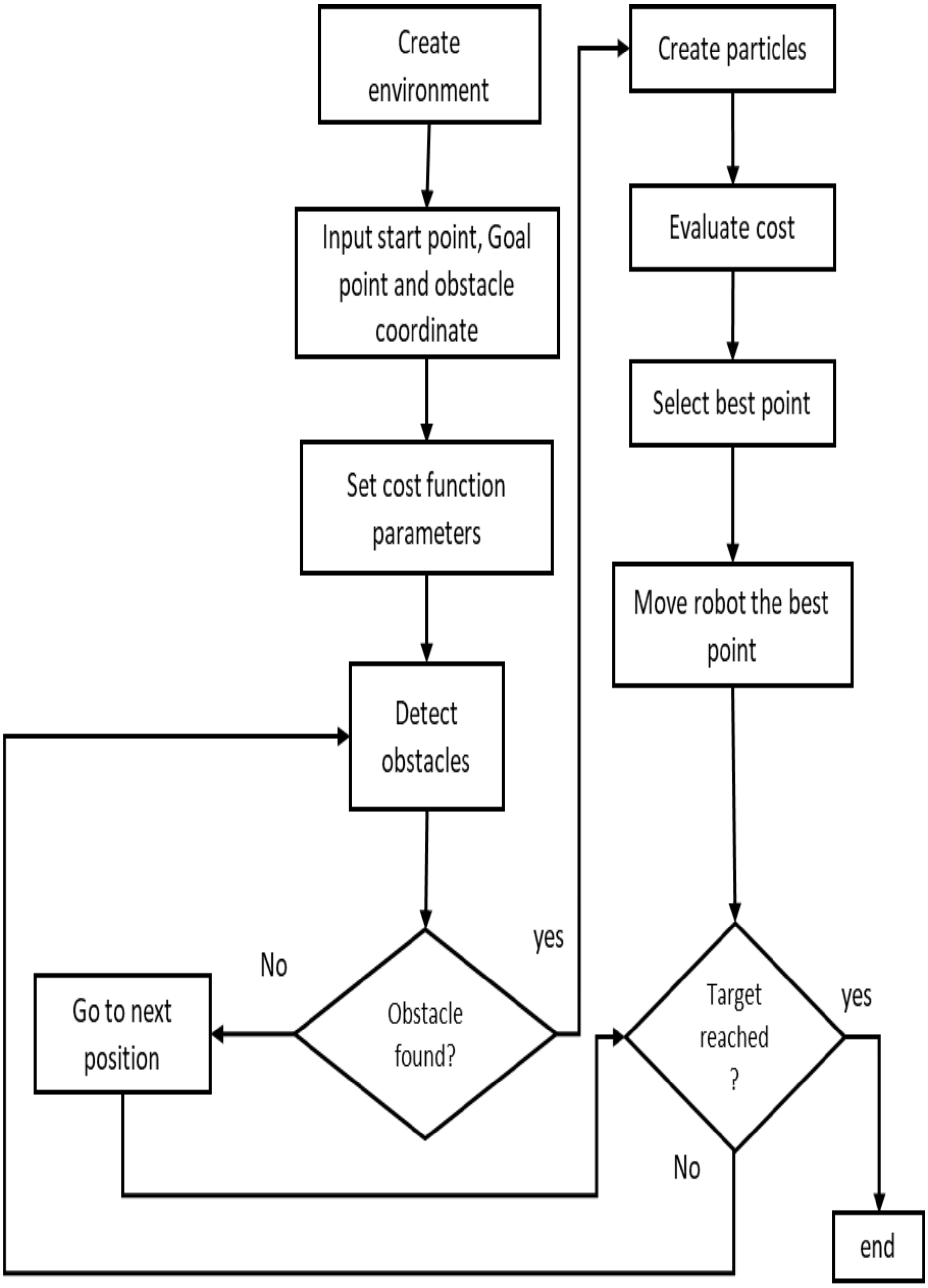

Figure 6. APF operation flowchart

Leader-Follower Formation Control with Virtual Leader

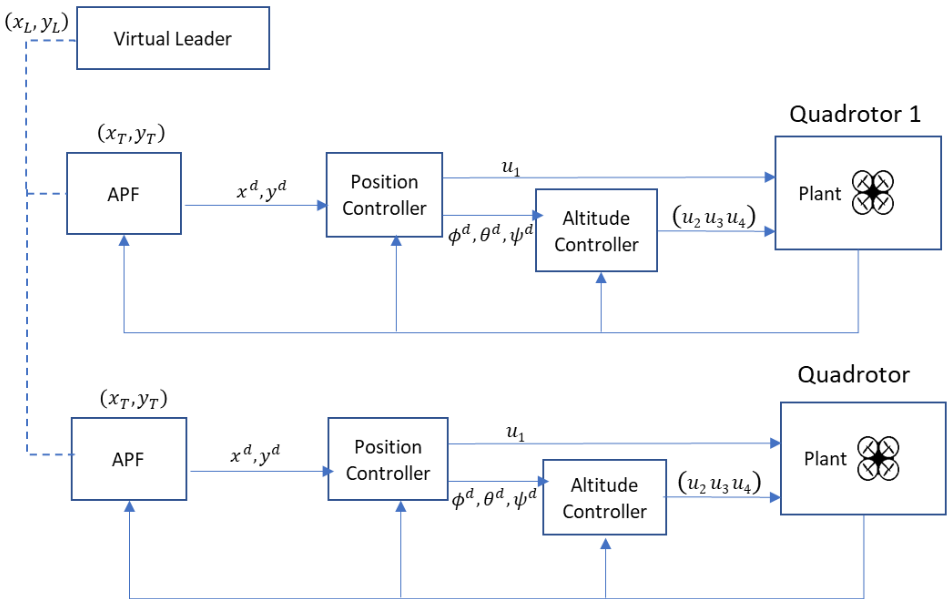

Figure 7. Block diagram of the overall formation control algorithm

Leader-follower approach is implemented as the formation control for the quadrotors' formation. The main process behind leader-follower method is the assigned leader flies according to the predefined trajectories with the help of trajectory tracking controller. Instead of using a physical leader, this study implements a virtual leader which provides an ideal predetermined path that will be followed by the following quadrotors. This virtual leader is more robust than using physical leader as single failure point is eliminated. The quadrotors that follow the virtual leader with certain offset are called followers. The formation is defined by certain offset given as follows:

$$x_T = x_L + x_f$$
$$y_T = y_L + y_f$$

where (x_L, y_L) is the virtual leader's coordinate, and (x_f, y_f) is the offset. The overall system is shown in Figure 8.

SIMULATION RESULTS

This section describes the performance of the proposed formation controller by implementing the algorithm in a MATLAB/Simulink simulation environment. The quadrotor model parameters are adopted from (Mahmood and Kim 2015) with $m = 0.4974$ kg, $I_x = 0.0086 \text{kg} \cdot \text{m}^2, I_y = 0.0086 \text{ kg} \cdot \text{m}^2, I_z = 0.0172 \text{kg} \cdot \text{m}^2$ and $a_g = 9.81 \text{ms}^{-2}$. Simulation results are shown in Figure 8 - Figure 10. Three quadrotors are simulated with triangular desired formation.

In case of no obstacle present, quadrotor formation using PID controllers for attitude/position controller, but without APF is shown in Figure 8. The quadrotors clearly were able to produce the formation while tracking the virtual leader. However, when the obstacle is present as shown in Figure 9, two of the quadrotors collide with the obstacles as they have no capability to avoid them.

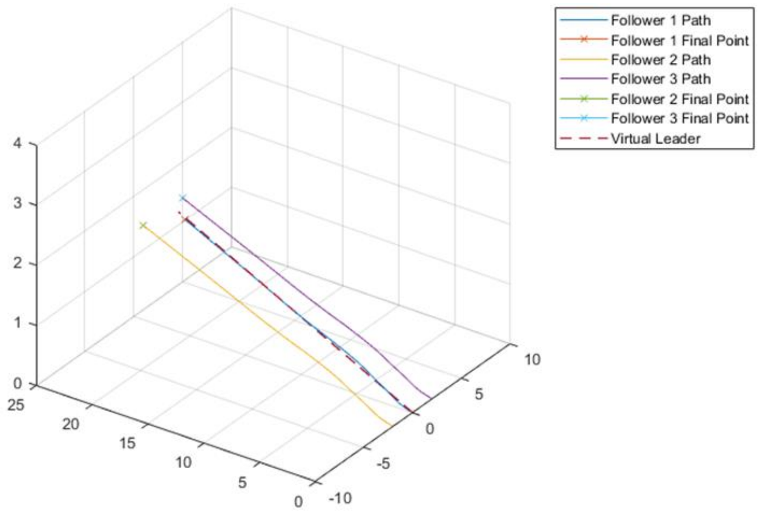

Figure 8 Formation of quadrotor without APF (no obstacle)

On the other hand, Figure 10 shows that the formation of the quadrotors is able to avoid collision in its path. On top of that, it is able to reconverge to its triangle formation as soon as the quadrotors no longer detect any obstacles. The three quadrotors in the formation are also able to generate the triangle shape at the destination. This proves that the proposed controller allows the quadrotors to produce and maintain the formation while avoiding collision with the obstacles.

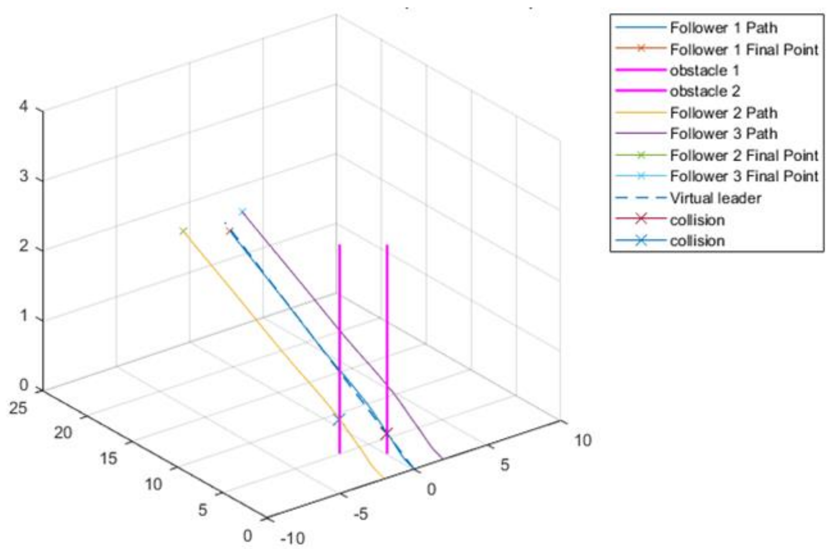

Figure 9 Formation of quadrotor without APF (with obstacle)

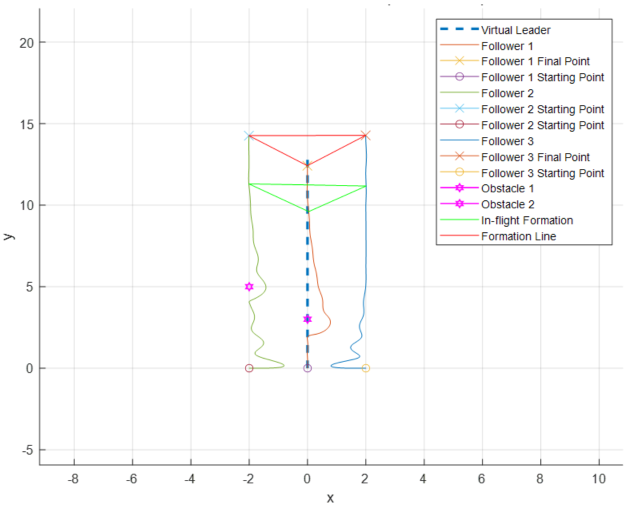

Figure 10 Formation of quadrotor using proposed controller (with obstacle)

CONCLUSION

This paper emphasizes on a single quadrotor control, formation control and collision avoidance path-planning. The formation control is made up of three follower quadrotors that follows a virtual leader path. The obstacle avoidance path planning using APF has successfully been demonstrated in the result. It is also proven that the usage of leader-follower with virtual leader can improve the trajectory of each follower. The PD controller used that is implemented is also able to demonstrate trajectory tracking with minimal error. The future work of this paper includes improvement on the APF algorithm and increasing the number of obstacles that can be avoided in the given environment.

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