ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Pigeon interaction mode switch-based UAV distributed flocking control under obstacle environments☆

Huaxin Qiu, Haibin Duan*

Key Laboratory of Virtual Reality Technology and Systems, School of Automation Science and Electrical Engineering, Beihang University (BUAA), Beijing 100083, PR China

ARTICLE INFO

Article history:
Received 1 December 2016
Received in revised form
8 March 2017
Accepted 20 June 2017

Keywords:
Unmanned aerial vehicle
Flocking control
Local minimum
Coordinated obstacle avoidance
Pigeon flock

ABSTRACT

Unmanned aerial vehicle (UAV) flocking control is a serious and challenging problem due to local interactions and changing environments. In this paper, a pigeon flocking model and a pigeon coordinated obstacle-avoiding model are proposed based on a behavior that pigeon flocks will switch between hierarchical and egalitarian interaction mode at different flight phases. Owning to the similarity between bird flocks and UAV swarms in essence, a distributed flocking control algorithm based on the proposed pigeon flocking and coordinated obstacle-avoiding models is designed to coordinate a heterogeneous UAV swarm to fly though obstacle environments with few informed individuals. The comparative simulation results are elaborated to show the feasibility, validity and superiority of our proposed algorithm.

1. Introduction

The unmanned aerial vehicle (UAV), an aircraft without a human pilot aboard, has received extensive attentions from researchers owning to superior performance in missions that are too "dull, dirty or dangerous" for humans [1–3]. According to Lanchester's laws, the number of UAVs is a more important factor to affect the combat power of a military force than the capability. Therefore, the usage of UAV swarms will be a better choice to control battle-field situations. Getting groups of UAVs to a swarm will require the design of distributed flocking control algorithms without huge computational overheads or large communication bandwidths.

Except traditional control algorithms [4–6], the swarm intelligence in multifarious complex systems, especially in bird flocks, has provided a novel but feasible thought for the UAV distributed flocking control due to their similarities: the stigmergy, no-center, simple individual and self-organization [7,8]. In the literature, a few researchers have made some exploratory attempts. Hauert et al. [9] demonstrated Reynolds' Boid model, the first flocking model which reveals the basic rules of bird flocking, with a swarm of small fixed-wing UAVs in outdoor experiments. Vásárhelyi et al. [10] implemented fundamental collective flight tasks with a multi-copter swarm based on the control algorithm which has a structure analogous to that of the Boid model. Saska [11] introduced a novel stabilization approach via the Boid model for a UAV swarm along a predefined path through obstacle environments. However, these methods have not considered the possibility that a swarm might consist of individuals with different capability levels.

As an added bonus, the problem has already appeared on the table of some researchers who are concerned about the collective motion mechanism of bird flocks. Ballerini et al. [12] discovered that each bird interacts on average with a fixed number of neighbors based on the egalitarian mode. Nagy et al. [13,14] found a hierarchical leadership network from multiple pigeon flock flights. In the hierarchy, pigeons follow the individuals in upper ranks and lead the flights of individuals in lower ranks. The stable leadership hierarchy is inferred to be the resultant of group coordination based on different individual competences [15]. Zhang et al. [16] discovered that pigeon flocks adopt a switching strategy between the hierarchy and egalitarian interaction modes. Each pigeon tends to follow the average of neighbors during smooth flights, whereas it switches to follow its leaders when sudden turns or zigzags occur.

This paper focuses on the distributed flocking control algorithm design for a heterogeneous UAV swarm under obstacle environments based on the pigeon interaction mode switch behavior. Firstly a pigeon flocking model is proposed based on the artificial

☆This work was partially supported by Natural Science Foundation of China (NSFC) under grant #91648205, # 61425008 and #61333004, Aeronautical Science Foundation of China # 2015ZA51013, and Academic Excellence Foundation of BUAA for Ph.D. Students.

* Corresponding author.
E-mail address: hbduan@buaa.edu.cn (H. Duan).

http://dx.doi.org/10.1016/j.isatra.2017.06.016
0019-0578/© 2017 ISA. Published by Elsevier Ltd. All rights reserved.

potential field method to allow a pigeon flock to safely fly to a target under obstacle environments. When flying based on the proposed flocking model, individuals may fall into local minimums of the potential field before reaching the final target. Fortunately, individuals are available to escape the local minimum by setting appropriate temporary targets [17]. Considering the different competences to avoid obstacles, a pigeon coordinated obstacle-avoiding model is presented based on the pigeon interaction mode switch behavior. Individuals equipped with more information about temporary targets will locate at more upper ranks in the hierarchy. Owing to the similarity between pigeon flocks and UAV swarms in mission requirements, the pigeon flocking and coordinated obstacle-avoiding models are applied to the control field to coordinate a heterogeneous UAV swarm to fly through a complex environment with obstacles. Some dynamic constraints of UAVs are considered to improve the practicality of the UAV distributed flocking control algorithm.

The rest of the paper is organized as follows. Section 2 models the collective motion of a pigeon flock to safely fly to a target under obstacle environments. Section 3 presents a coordinated obstacle-avoiding model based on the pigeon interaction mode switch behavior in consideration of the different individual obstacle-avoiding competence. Section 4 describes a UAV model. Section 5 proposes a distributed flocking control algorithm for a UAV swarm based on the pigeon flocking and coordinated obstacle-avoiding models. Comparative simulations are elaborated in Section 6, and our concluding remarks are drawn in Section 7.

2. Pigeon flocking model

The organized flight of pigeon flocks in the sky is seemingly a well-rehearsed group dance. The complex collective behavior arises from simple local interaction rules that an individual conducts cohesion, alignment and separation based on the states of its flockmates. The flockmate selection are considered to involve two interaction modes: the egalitarian interaction mode and hierarchical interaction mode. In the former mode, each pigeon interacts within a fixed neighborhood region (FNR) or with a fixed number of neighbors (FNN). In the latter mode, each pigeon follows the individuals with upper ranks in the hierarchical leadership network. A switching strategy is employed by each pigeon to balance the two apparently contradictory interaction modes: Each pigeon adopts the egalitarian interaction mode during smooth flights, whereas it switches to the hierarchical interaction mode when sudden turns or zigzags occur. In this section, a pigeon model is proposed without regard for the switching strategy in pigeon flocks.

Consider N pigeons flying in Euclidean 3-spaces with M obstacles, and the dynamic model of each individual regarded as one mass point is as the following equation:

$$\begin{cases} \dot{\boldsymbol{X}}^i = \boldsymbol{v}^i \\ m^i\dot{\boldsymbol{v}}^i = \boldsymbol{u}^i - k^i\boldsymbol{v}^i,\ i = 1, \ldots, N \end{cases} \tag{1}$$

where $m^i > 0$ is the mass of each individual and set to be $1kg$ in this paper, $\boldsymbol{X}^i, \boldsymbol{v}^i, \boldsymbol{u}^i \in \mathbb{R}^3$ are the position vector, velocity vector and control input of each individual respectively, $k^i > 0$ is the gain of velocity attenuation and $-k^i\boldsymbol{v}^i$ is the velocity damping which is equivalent to air resistances.

The control input of each individual is as the following equation:

$$\boldsymbol{u}_l^i = \begin{cases} f_f + f_t + f_o + f_c + f_{a\_vn} + f_{a\_ve} + k^i\boldsymbol{v}_l^i, & l = 1, 2 \\ f_{a\_h_e} + f_{a\_ve} + k^i\boldsymbol{v}_l^i, & l = 3 \end{cases} \tag{2}$$

where $l = 1, 2, 3$ respectively correspond to the x-axis, y-axis and z-axis directions of the inertial coordinate system and the formation control component f_f is as the following equation:

$$f_f = K_f\left(\sum_{j\in\left\{\left\|\boldsymbol{X}_{1,2}^{ji}\right\|\le R_{comm.}\right\}} w_j\nabla\left\|\boldsymbol{X}_{1,2}^{ji}\right\|P_f^{ji}\right)\Bigg/\sum_{j\in\left\{\left\|\boldsymbol{X}_{1,2}^{ji}\right\|\le R_{comm.}\right\}} w_j \tag{3}$$

where $K_f > 0$ is the gain of formation control, $\left\|\boldsymbol{X}_{1,2}^{ji}\right\|$ is the horizontal distance between individual i and j, w_j is the influence weight of individual j to individual i, $R_{comm.}$ is the horizontal communication range and the potential function P_f^{ji} for formation control in this paper is as the following equation:

$$P_f^{ji}\left(\left\|\boldsymbol{X}_{1,2}^{ji}\right\|\right) = \frac{1}{2}\left\|\boldsymbol{X}_{1,2}^{ji}\right\|^2 - (R_{desire})^2\cdot Ln\left\|\boldsymbol{X}_{1,2}^{ji}\right\| \tag{4}$$

where R_{desire} is the expected horizontal distance between individual i and j.

The migration control component f_t is as the following equation which leads each individual to target $\boldsymbol{T}$:

$$f_t = \begin{cases} K_t\nabla_{(\boldsymbol{T}_l-\boldsymbol{X}_l^i)}P_t, & \left|\boldsymbol{T}_l - \boldsymbol{X}_l^i\right| > R_{\lim 1} \\ 0, & \left|\boldsymbol{T}_l - \boldsymbol{X}_l^i\right| \le R_{\lim 1} \end{cases} \tag{5}$$

where $K_t > 0$ is the attraction gain of the target, the potential function P_t of the target in this paper is $\left|\boldsymbol{T}_l - \boldsymbol{X}_l^i\right|^3/3$ and $R_{\lim 1}$ is the limited distance of potential field influence of the target.

The control component f_o of obstacle avoidance is as the following equation:

$$f_o = K_o\sum_{j'\in\left\{\rho(\boldsymbol{X}^i,\boldsymbol{obs}_{j'})\le R_{sense}\right\}} \nabla_{\boldsymbol{X}^i}P_o^{j'} \tag{6}$$

where $K_o > 0$ is the repulsion gain of obstacles, $\rho(\boldsymbol{X}^i, \boldsymbol{obs}_{j'})$ is the shortest distance between individual i and obstacle j', $\boldsymbol{obs}_{j'}$ is the position vector of the point closest to individual i on the surface of obstacle j', R_{sense} is the limited distance of potential field influence of the obstacle j' and the potential function $P_o^{j'}$ of the obstacle j' in this paper is as the following equation:

$$P_o^{j'} = -\frac{1}{\rho(\boldsymbol{X}^i, \boldsymbol{obs}_{j'})} - \frac{2}{R_{sense}}Ln(\rho(\boldsymbol{X}^i, \boldsymbol{obs}_{j'})) + \frac{1}{(R_{sense})^2}\rho(\boldsymbol{X}^i, \boldsymbol{obs}_{j'}) \tag{7}$$

The following equation can be obtained by substituting Eq. (7) into Eq. (6):

$$f_o = K_o\sum_{j'\in\left\{\rho(\boldsymbol{X}^i,\boldsymbol{obs}_{j'})\le R_{sense}\right\}}\left(\frac{1}{\rho(\boldsymbol{X}^i, \boldsymbol{obs}_{j'})} - \frac{1}{R_{sense}}\right)^2\frac{\partial\rho(\boldsymbol{X}^i, \boldsymbol{obs}_{j'})}{\partial\boldsymbol{X}^i} \tag{8}$$

where $\frac{\partial\rho(\boldsymbol{X}^i,\boldsymbol{obs}_{j'})}{\partial\boldsymbol{X}^i}$ can be represented as

$$\frac{\partial\rho(\boldsymbol{X}^i, \boldsymbol{obs}_{j'})}{\partial\boldsymbol{X}^i} = \frac{\boldsymbol{X}^i - \boldsymbol{obs}_{j'}}{\rho(\boldsymbol{X}^i, \boldsymbol{obs}_{j'})} \tag{9}$$

The control component f_c is to avoid the collision between individuals. In this paper, the expression of f_c is similar to f_o:

Please cite this article as: Qiu H, Duan H. Pigeon interaction mode switch-based UAV distributed flocking control under obstacle environments. ISA Transactions (2017), http://dx.doi.org/10.1016/j.isatra.2017.06.016