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On V-shaped Flight Formation of Bird Flocks with Visual Communication Constraints

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Abstract— **This paper aims at investigating how to form a V-shaped flight formation (V formation) observed in bird flocks from a control engineering perspective. Other than standard considerations of energy consumptions and collision avoidance, the well-known biologically realistic perception model in terms of the visual communication constraints is also investigated in this paper. By incorporating the visual communication constraints into the cost function, a standard gradient-based control algorithm can form the formation. A large amount of simulations suggest that by carefully adjusting the visual communication constraints in the cost function, V formation is formed as observed bird flocks.**

I. Introduction

The phenomena of organized group behaviors, such as flocking of large numbers of small birds like pigeons or blackbirds as well as fish, herds, and crowds, have fascinated many researchers recently [1], [2]. Mathematicians and control engineers have focused on the theoretical development of the self-organized cooperation among individuals and have revealed that complicated collective behaviors of animals are usually obtained as a result of some simple individual rules, for example the well-known Reynolds rules: cohesion, separation, and alignment [3], [4]. These theoretical results lead to a large number of successful engineering applications from cooperative control of unmanned aerial vehicles (UAVs) [5] to self-deployment of mobile sensor networks [6].

This paper focuses on a special group behavior: the distinctive V-shaped formation or V formation of bird flocks that has been an active research topic in biology for last 30 years [1], [2], [3], [4], [7]. There are two major factors that contribute to the V formation. As discussed in [8], [9], [10], aerodynamics will affect the energy consumption. In particular, in [9], a model is proposed to characterize the behavior of such aerodynamics. Another important factor is the visual communication constraints. For a group of birds with the fixed position of the eyes in the heads and the same orientation, flying in staggered line can achieve unhindered visual communication and avoid collisions with each other [11], [12].

Other than biologists, control engineers are interested in understanding the V formation. In [13], the principles that steer birds to the V formation are summarized as three rules: coalescing (flock), gap-seeking (afford some unobstructed view in the flight direction), and stationing (position itself in the regions of upwash). In [14], the line formation is formed by two stages: the rule-based initiation stage and the steady-flight stage with an energy-savings model. In addition, the approach based on fuzzy logic rules is presented in [15]. The self-organizing phenomenon of formation flight is discussed in [8]. The inherent difficulty in tracking the lateral position of birds in V formation is explained from the viewpoint of control theory [16]. In [9], the diffusion Least Mean Squares (LMS) algorithm based on the principle of energy saving is proposed to form a stable V formation of bird flocks without considering the dynamics of each bird. Moreover, the rigorous analysis for forming formation is missing.

Motivated by the results obtained in [9], this paper aims at providing a systematic analysis of the V formation from control engineering perspective: a group of agents (or birds) work together cooperatively to achieve some optimal group performance. As noted in [11], [16], [17], the dynamics of each agent are characterized by the model of fixed-wing aerial vehicle flying on the constant altitude. Other than only minimizing the energy consumption of the group, visual communication constraints and collision avoidance are considered as parts of the global cost. To the best of authors' knowledge, it is the first time that visual communication constraints are considered in the theoretical analysis of V formation. With the help of this novel global cost function, a distributed gradient-like control algorithm is thus proposed. Our main result (Theorem 1) shows that a stable formation is thus formed. It is also observed from a large amount of simulations that by carefully designing the cost with respect to the communication constraints, the V formation indeed is formed. Our future work will further explore this novel cost function in order to provide sufficient conditions to generate the V formation.

II. Models and Cost Functions

A. A Simplified Model of Bird Dynamics

The flight behavior of birds is quite complicated if the quantitative effects of the featured wing flapping are considered [7], [18]. However, it is observed that these V formations usually have a typically two-dimensional characteristics [14]. As noted in [11], [16], the model based on a fixed

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wing flight is valid for relatively large birds in steady flight with low wingbeat frequency. Therefore, by assuming that all birds fly in the same horizontal plane and wing movements are negligible, the model of fixed-wing aerial vehicle flying on the constant altitude [17] is used to to describe the dynamics of the i^{th} bird of a group with N birds:

$$\begin{cases} \dot{x}_i = v_i \cos\theta_i \\ \dot{y}_i = v_i \sin\theta_i \\ \dot{\theta}_i = \omega_i, \end{cases} \tag{1}$$

where x_i and y_i represent the 2-D Cartesian coordinates of the mass center of the i^{th} bird and θ_i is it's heading angle. The variables v_i and ω_i denote the linear velocity and angular velocity respectively. They are the control inputs to be designed. For simplicity, it is denoted that $p_i = [x_i, y_i]^T \in \mathbb{R}^2$, representing the relative position of the i^{th} bird in the constant flight altitude. Denoting $z_i = [x_i, y_i, \theta_i]^T$, then the group state can be described by $z = [z_1, z_2, \cdots, z_N]^T$, $x = [x_1, x_2, \cdots, x_N]^T$, $y = [y_1, y_2, \cdots, y_N]^T$, and $\theta = [\theta_1, \theta_2, \cdots, \theta_N]^T$. Let assume that each bird has a limited distance of view R_s, which implies that bird i can obtain the information of its flockmates in the set $N_i = \{j \in \mathscr{V} | \|z_j - z_i\| < R_s, j \neq i\}$, where $\mathscr{V}$ is the set of birds.

B. Cost functions

Generally, it is believed that the global behavior of a group of agents is related to some global cost [19]. As already highlighted, forming V formation will lead to maximize energy saving for the group, minimize visual communication hindrance and avoid collisions. Thus it is quite natural to assume that the global cost is related to energy, visual communication constraints and collision avoidance. This subsection provides more details about three factors.

1) Energy consumption: As discussed in [8], [9], [10], during birds' flight, the difference in the pressure of air above and below the wings causes a pair of trailing vortices behind the two wingtips. The oppositely rotating trailing vortices create a downwash right behind the bird body which will increase the induced drag for the bird flying in that area, and also produce two upwashes outside the vortices, which will reduce energy consumption as can be seen in Fig.1.

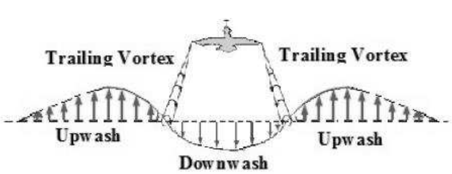

Fig. 1. Trailing vortices and the related regions of upwash and downwash generated by the flight of a bird.

The upwash or downwash produced by a bird's flight depends on vortex circulation, bird wingspan, and the relative position to the centroid of the bird, denoted by $[\triangle x, \triangle y]^T$, etc. For the sake of clarify, we use the model used in [9] to model the airflow (upwash or downwash) velocity v_a induced by the vortex.

$$v_a(\triangle x, \triangle y) = \frac{\Gamma}{2\pi}\left(\frac{\triangle x - a/2}{r_c^2 + (\triangle x - a/2)^2} - \frac{\triangle x + a/2}{r_c^2 + (\triangle x + a/2)^2}\right) \left(1 - \frac{\triangle y}{\sqrt{\triangle y^2 + (b/2)^2}}\right) e^{-\frac{(\triangle y + \beta)^2}{2\sigma^2}}, \tag{2}$$

where Γ is the vortex circulation in m^2/s, r_c is the core radius, b is the wingspan of the bird, and a is the separation between the trailing vortices. Usually it is assigned with $a = b\pi/4$ [18]. Moreover, the Gaussian term $e^{-\frac{(\triangle y+\beta)^2}{2\sigma^2}}$ is employed to mimic the strength decay of vortex along the y direction. In [9], the meanings of β and σ are discussed. Obviously, when $\triangle y \to \infty$, this velocity v_a tends to zero.

In order to model behavior for birds in downwash and upwash, we consider a bird located at $[\triangle x, \triangle y]^T$ and integrate the airflow velocity along its wingspan and dividing by b as in [9] to describe the comprehensive influence that it encounters

$$\begin{aligned} f_0(\triangle x, \triangle y) &= \frac{1}{b}\int_{\triangle x - \frac{b}{2}}^{\triangle x + \frac{b}{2}} v_a(\eta, \triangle y) d\eta \\ &= \frac{\Gamma}{4\pi b}\left(\ln\frac{(\triangle x - \frac{a}{2} + \frac{b}{2})^2 + r_c^2}{(\triangle x - \frac{a}{2} - \frac{b}{2})^2 + r_c^2} - \ln\frac{(\triangle x + \frac{a}{2} + \frac{b}{2})^2 + r_c^2}{(\triangle x + \frac{a}{2} - \frac{b}{2})^2 + r_c^2}\right) \\ &\quad \left(1 - \frac{\triangle y}{\sqrt{\triangle y^2 + (\frac{b}{2})^2}}\right) e^{-\frac{(\triangle y + \beta)^2}{2\sigma^2}}. \end{aligned} \tag{3}$$

If the function $f_0(\triangle x, \triangle y)$ is positive, it indicates a lifting force to the trailing bird to save the energy. On the contrary, the energy consumption will increase compared with flying alone if $f_0(\triangle x, \triangle y) < 0$. Some typical properties of $f_0(\triangle x, \triangle y)$ is summarized as follows.

1 : $f_0(-\triangle x, \triangle y) = f_0(\triangle x, \triangle y)$, for any $(\triangle x, \triangle y) \in R^2$;

2 : There exists a positive pair $(\triangle x^*, \triangle y^*)$ such that $f_0(-\triangle x^*, \triangle y^*) = f_0(\triangle x^*, \triangle y^*) \geq f_0(\triangle x, \triangle y)$ for any $(\triangle x, \triangle y) \in R^2$;

The above characteristics of $f_0(\triangle x, \triangle y)$ can be also illustrated in Fig. 2 with $\Gamma = 100$, $b = 1$, $r_c = 0.15$, $\beta = 0.7$, and $\sigma = 2$.

Remark 1: Obviously, the function $f_0(\triangle x, \triangle y)$ is symmetric with repsect to y-axis with two maxima in pairs. Therefore, from the energy saving perspective, the trailing bird will attempt to fly at the position $[-\triangle x^*, \triangle y^*]$ or $[\triangle x^*, \triangle y^*]$. ∘

It is denoted that the energy required for a bird to fly by iteself as E_0. Let us consider that a group of N birds fly at the position $[x_i, y_i]^T$, $i = 1, ..., N$ in the same horizontal plane. Then the corresponding energy for the i^{th} bird can be represented as:

$$E_i(x_i, y_i) = E_0 - k_e \sum_{j=1}^{N} f_0(x_i - x_j, y_i - y_j) \tag{4}$$