Bee-Dance-Inspired UAV Trajectory Pattern Design for Target Information Transfer without Direct Communication

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Abstract: The deployment of robot swarms that perform a task cooperatively is attracting more and more attention in these years. There is a big challenge for existing methods to transfer information without direct communication. In this work, inspired by the phenomenon of bee swarm convening recruits to the food resource with waggle dance, we present a behavior-based approach to transfer information, using the UAV's trajectory pattern rather than direct communication. Two trajectory patterns are designed to transfer information. Furthermore, both of them are optimized subject to the constraint on UAVs. We show that both patterns are feasible through simulation, and the 8-type performs better than the b-type under given indexes. Our information transfer strategy can be used for search and rescue in extreme environments and other communication-denied scenarios to meet the transmission needs of target position information.

Key Words: Swarm robotics, Trajectory, Pattern, Non-communication, Search and rescue, Waggle dance

1 Introduction

Unmanned aerial vehicles (UAVs) perform a more and more critical role in recent years. Because of the characteristics of convenience and efficiency, UAVs bring new potentialities in complex mission scenarios, such as search and rescue, surveillance, and monitor natural disasters. In this paper, we consider an extreme search and rescue scenario. For example, in a harsh environment that is not conducive to radio communication, a UAV needs to transfer the target information with others. Hence, there is a big challenge for existing methods of information transmission without direct communication.

The current swarm robotics strategies mainly rely on unlimited or limited direct communication. In the collective foraging task, some forms of communication are necessary among individuals due to cooperation [1]. A cooperative search framework is proposed in [2], in which each UAV collects information from sensors and exchanges the search map periodically. The study in [3] presents a cooperative search methodology for UAV swarms effective against evading targets, requiring minimal communication. The shared memory can also be used to build a shared map, which makes robots follow the same path or avoid different goals from getting in each other's way [4]. However, the cluster of multi-UAV calls for strategies with fewer communication overheads. There are currently some researches on solving the problem without direct communication. For example, in [5], a homogeneous swarm of robots is assigned and reassigned to multiple locations without inter-agent wireless communication. And the study in [6] investigates partial collective decision-making in a robot swarm with no direct communication allowed. In [7], a stable aggregation of a swarm is completed using only local sensing and no inter-agent communication.

Biological behavior is another interesting topic. Many hard-to-solve problems take inspiration from natural self-organizing systems like social insects and bird flocks [8]. The studies in [9-11] adopt the strategies of ants and bees in the foraging activity. The ant deposits a pheromone, and recruits follow that chemical trail. Corresponding to this is the honeybee's dance language to transfer the food source's information through stylized dance. To some extent, neither of these two strategies uses direct communication, which means they are suitable for communication-denied environments. These biological behaviors give us a different way to solve the problem. The study in [12] proposes a communication system that mimics the honey bee's waggle dance, with three fundamental geometric patterns but not complex behavioral patterns representing both direction and distance information.

Consider the need for transferring information from one UAV to other UAVs without direct communication, like the extreme search and rescue scenario in harsh environments. For the sake of simplicity, we call the UAV with known information *the recruiter* and the UAVs performing normal tasks *the recruited* imitating the bee. This paper aims to design proper patterns, which help the recruiter share information about the target to the recruited based on behavior. The first task we meet is identifying the recruiter. Equipped with lights of different colors means the particular requirements for the initial configuration and the additional cost. Considering the characteristic of UAVs flying in the sky, we can use the natural height information. In other words, the recruited flies above the recruiter. UAVs above can observe the recruiter, while the recruiter can use the detection equipment to get the recruited's position. In this way, the recruiter can perform a unique pattern to transfer the information. Our innovation is to solve this problem based on biological behavior while bypassing the restrictions of direct communication. Concretely, the contribution relies on two designed trajectory patterns encoding the target position information. This behavior-based method is applicable to the communication-denied occasion for UAVs.

2 Problem Formulation

In this section, we build the models of observation and flight constraint separately as below. Then, the information transfer problem without direct communication is formulated.

2.1 Observation Model of the Recruited UAVs

The recruited UAVs are mounted with down-looking imaging equipment. We assume that the sensing information is accurate within the recruited's perception range, namely, the recruited can capture what happened below. If the recruiter is within this perception range, it can be observed by the recruited.

Moreover, the recruited UAVs are in a formation with the same altitude and the uniform velocity $\mathbf{v}_0 \in \mathbb{R}^2$ in a horizontal plane. For the sake of simplicity, we present two coordinate systems. The first is $O_G - X_G Y_G Z_G$, which denotes the ground coordinate system. And the second is $O_F - X_F Y_F Z_F$, which denotes the formation coordinate system. The formation coordinate system takes the center of the recruited as the origin and is parallel to the ground coordinate system. Below the recruited, as shown in Fig. 1, there is a common observation area denoted by A for all recruited UAVs. Here, $A \subset \Pi : z_F = -h_0$, where $h_0 > 0$. To grasp the problem's essence, we regard the common part as a limited area for the recruiter.

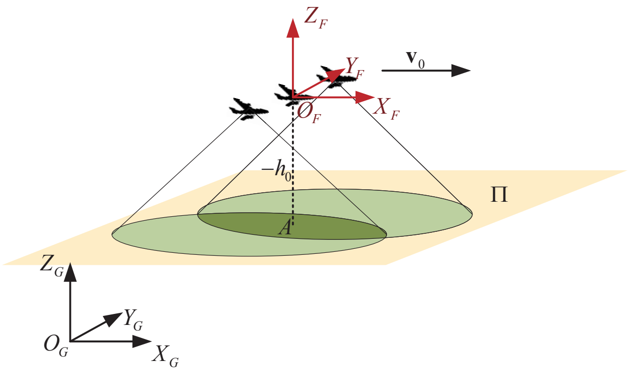

Fig. 1: Multi-UAV observation model.

2.2 Flight Constraint Model of Recruiter UAV

We simplify the flight model for the fixed-wing "recruiter" and only consider the speed constraint and the turning radius constraint. Its speed v has the relationship as

$$v_{\min} \leq v \leq v_{\max} \tag{1}$$

where $v_{\min} > 0$ and $v_{\max} > 0$ are the minimum and maximum of the recruiter's speed. And due to the constraint of the UAV itself, the curvature k of actual flight trajectory satisfies the constraint as

$$k \leq \frac{1}{r_{\min}} \tag{2}$$

where $r_{\min}$ is the minimum turning radius. When the trajectory $\mathcal{C}$ is represented by the time parameter t as $\mathbf{q} = \mathbf{q}(t)$. The formula for curvature $k(t)$ is

$$k(t) = \frac{\|\dot{\mathbf{q}}(t) \times \ddot{\mathbf{q}}(t)\|}{\|\dot{\mathbf{q}}(t)\|^3}. \tag{3}$$

2.3 Information Transfer Problem without Direct Communication

From the biological foundations of swarm intelligence, we learn several excellent recruitment mechanisms. The bee performs the waggle dance to convey the information about targets located far away from the hive [13]. Inspired by the dance language strategy, our objective is to propose the pattern that encodes spatial information. To make the identification process simpler, the recruiter performs a uniform speed v_1 within observation area A. And the main problems are stated in the following.

Under assumptions before, the first problem here is to determine which kind of spatial pattern can transfer the message in the plane Π. Due to the possible interference, the recruiter needs to perform the trajectory several times continuously. In order to keep the recruiter within the recruited's field of view, the trajectory $\mathcal{C}$ must be designed as a closed curve. The closed curve starts and ends at the same point, belonging to the observation area A as

$$\mathcal{C} \subset A \subset \Pi \subset \mathbb{R}^2. \tag{4}$$

The recruiter performs this closed curve at a constant relative speed v_1 in $O_F - X_F Y_F Z_F$. At the same time, the recruiter's actual flight must satisfy the flight constraint model in $O_G - X_G Y_G Z_G$ mentioned in Section 2.2.

In this process, the second question of how to measure the pattern design has arisen. The most critical index we value is the time cost. For a time-related closed curve $\mathcal{C}$, the time cost can be calculated as

$$t = \frac{\int_{\mathcal{C}} \mathrm{d}s}{v_1} \tag{5}$$

where v_1 is the constant relative speed with instantaneous direction changing over time, and ds is the length microelement. When the time cost is optimal, we also discuss energy consumption. A UAV energy consumption model is described in [14]. For fixed-wing UAVs with level flight under normal operations (there is no reverse thrust caused by abrupt deceleration), we can easily evaluate whether a trajectory pattern has high energy efficiency with this UAV energy consumption formula.

3 Trajectory Pattern Design

3.1 Pattern Design

Inspired by the bee's waggle dance, the first pattern we propose is the 8-type. The ratio of two circle diameters is regarded as the description of distance, and the principal axis of the "8" represents the direction of the target. As shown in Fig. 2, the value $a > 0$ and $b > 0$ here are the diameters of the smaller and larger circles in the 8-type, respectively. And the distance can be calculated as

$$d = \frac{b}{a} c \tag{6}$$

where $c > 0$ is the pre-set parameter related to the size of the area.

Similar to the number "8", we develop another b-type to transfer the target's distance and direction information. We use the ratio of straight-line and circle diameter as the description of distance, and the orientation of the "b" represents the direction of the target. As shown in Fig. 3, the symbol a and b are the diameters of the circle and the length of the straight line in the b-type, respectively. The distance from the information transfer point to the target can be calculated using Equ. (6). And the details of the value of a and b should be given according to the specific situation.

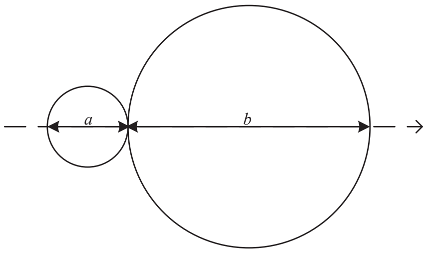

Fig. 2: The 8-type trajectory pattern.

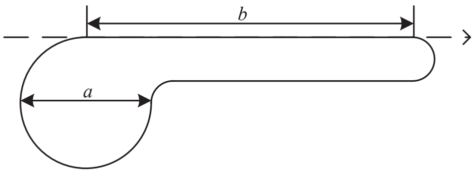

Fig. 3: The b-type trajectory pattern.

3.2 Design Constraint

Since the fixed-wing UAVs above are not stationary, the principle of velocity superposition is used as

$$\mathbf{v}(t) = \mathbf{v}_0 + \mathbf{v}_1(t) \tag{7}$$

where $\mathbf{v}_0$ is a constant vector representing the recruited's velocity in $O_G{-}X_GY_GZ_G$, and the vector $\mathbf{v}_1(t)$ is the recruiter's velocity in $O_F{-}X_FY_FZ_F$. The vector $\mathbf{v}(t)$ is the velocity of the recruiter in the ground coordinate system. The recruiter performs unique pattern in the view of recruited, and its actual velocity satisfies the speed superposition principle. For the fixed-wing UAVs, there is an inherent constraint on the minimum turning radius. Consider a circular relative motion, and we find that the recruiter should follow *Theorem 1* and *2* below.

If the radius R of the circular relative motion is known, the relative speed v_1 must satisfy the constraint as *Theorem 1*, where $v_1 = \|\mathbf{v}_1(t)\|$. Besides, we have $v_0 = \|\mathbf{v_0}(t)\|$ in *Theorem 1*.

Theorem 1. Suppose the recruiter performs a uniform circular motion with the radius R in the formation coordinate $O_F{-}X_FY_FZ_F$. If the relative speed v_1 satisfies $\frac{2\pi R}{t_{\max}} < v_1 \leq \min\{v_{\max} - v_0, v_0 - v_{\min}\}$, then Equ. (2) holds. Here $v_{\min}$ and $v_{\max}$ are the extreme values of the recruiter's speed, and $t_{\max}$ is the maximum time cost of the whole process.

Proof. Considering a uniform circular relative motion trajectory in the formation coordinate $O_F{-}X_FY_FZ_F$, the relative velocity v_1 should make v satisfy the minimum turning radius and time constraint. According to the vector triangle inequality, given two vectors $\mathbf{u}$ and $\mathbf{v}$, we have

$$|\|\mathbf{u}\| - \|\mathbf{v}\|| \leq \|\mathbf{u} \pm \mathbf{v}\| \leq \|\mathbf{u}\| + \|\mathbf{v}\|. \tag{8}$$

Because the UAV flies at a constant speed but with varying headings in the uniform circular motion, the recruiter's actual speed v satisfies

$$|v_0 - v_1| \leq v \leq v_0 + v_1. \tag{9}$$

And the turning radius has a relationship with the speed and load factor n as

$$r = \frac{v^2}{g\sqrt{n^2 - 1}} \tag{10}$$

$$n = \frac{1}{\cos\phi} \tag{11}$$

where g is the gravitational acceleration and ϕ is the roll angel. The minimum actual speed $|v_0 - v_1|$ corresponds to the minimum turning radius, so

$$\frac{(v_0 - v_1)^2}{g\sqrt{{n_{\max}}^2 - 1}} \geq \frac{{v_{\min}}^2}{g\sqrt{{n_{\max}}^2 - 1}}. \tag{12}$$

To make the UAV's flight feasible, we should make

$$v_0 \geq v_1 \tag{13}$$

and the inequality (12) can be reduced to

$$v_1 \leq v_0 - v_{\min}. \tag{14}$$

Since the actual speed is less than or equal to the maximum speed $v_{\max}$, we can get

$$v_0 + v_1 \leq v_{\max}. \tag{15}$$

Because the process has time constraint, the relationship can be expressed as

$$\int_0^{t_1} v_1 \mathrm{d}t = 2\pi R \tag{16}$$

$$t_1 = \frac{2\pi R}{v_1} \leq t_{\max} \tag{17}$$

where t_1 is the time cost of the whole flight, R is the radius of relative uniform circular motion.

As a result, the relative speed v_1 has the constraint as

$$\frac{2\pi R}{t_{\max}} < v_1 \leq \min\{v_{\max} - v_0, v_0 - v_{\min}\}. \tag{18}$$

□

In the following, we will further discuss radius R. As for the situation of the relative motion's radius R is unknown while the relative speed v_1 is known, R should satisfy the constraint below. We assume that the recruited perform a uniform linear motion in speed v_0, so the actual trajectory of the recruited has the period T. The symbols x_1, y_1 are the relative motion displacements in the formation coordinate system, x_0, y_0 and x, y are the actual displacement of the recruited and recruiter in the ground coordinate respectively. The recruiter and recruited obey the following motion formulas as

$$x_1 = R\cos\theta, y_1 = R\sin\theta \tag{19}$$

$$x_0 = v_0 t\cos\delta, y_0 = v_0 t\sin\delta \tag{20}$$

where δ is the angle between the recruited's direction and the x-axis. Differentiate both sides of Equ. (19) and (20), and we can obtain

$$\mathrm{d}x_1 = R(-\sin\theta)\,\mathrm{d}\theta, \mathrm{d}y_1 = R\cos\theta\mathrm{d}\theta \tag{21}$$

$$\mathrm{d}x_0 = v_0\cos\delta\mathrm{d}t, \mathrm{d}y_0 = v_0\sin\delta\mathrm{d}t \tag{22}$$

where θ is the angle of relative uniform circular motion. Putting $\mathrm{d}\theta = \frac{v_1}{R}\mathrm{d}t$ into (21), and by using the principle of superposition, we get

$$\mathrm{d}x = R\left(-\sin\left(\frac{v_1}{R}t\right)\right)\frac{v_1}{R}\mathrm{d}t + v_0\cos\delta\mathrm{d}t \tag{23}$$

$$\mathrm{d}y = R\cos\left(\frac{v_1}{R}t\right)\frac{v_1}{R}\mathrm{d}t + v_0\sin\delta\mathrm{d}t \tag{24}$$

and

$$\dot{x}(t) = -v_1\sin\left(\frac{v_1}{R}t\right) + v_0\cos\delta \tag{25}$$

$$\dot{y}(t) = v_1\cos\left(\frac{v_1}{R}t\right) + v_0\sin\delta \tag{26}$$

$$\ddot{x}(t) = -\frac{v_1^2}{R}\cos\left(\frac{v_1}{R}t\right) \tag{27}$$

$$\ddot{y}(t) = -\frac{v_1^2}{R}\sin\left(\frac{v_1}{R}t\right). \tag{28}$$

Consider a two-dimensional situation, in which the trajectory can be described as

$$\mathbf{q}(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} \tag{29}$$

where $\mathbf{q}(t)$ is expressed in the ground coordinate system. It is obvious that the parameters R and t are variables of the curvature k. Then, Equ. (3) can be written as

$$k(R,t) = \frac{|\dot{x}(t)\ddot{y}(t) - \dot{y}(t)\ddot{x}(t)|}{(\dot{x}^2(t) + \dot{y}^2(t))^{\frac{3}{2}}} \tag{30}$$

and the curvature $k(R,t)$ satisfies the constraint as

$$k(R,t) \le \frac{1}{r_{\min}}. \tag{31}$$

Given any time t_0, there exists a critical relative motion's radius $R_{t'}$ in the time $t' \in [t_0, t_0 + T]$, which satisfies

$$k(R_{t'}, t') = \frac{1}{r_{\min}}. \tag{32}$$

Because the curvature and the radius of curvature are in reciprocal relationship, R should be greater or equal to $\sup\limits_{t' \in [t_0, t_0+T]} R_{t'}$. Considering the time constraint in inequality (17), we can get the range of R

$$R \in \left[\sup_{t' \in [t_0, t_0+T]} R_{t'}, \frac{v_1 t_{\max}}{2\pi}\right]. \tag{33}$$

So for the situation of the relative motion's radius R is unknown while the relative speed v_1 is known, the pattern design needs to satisfy *Theorem 2*.

Theorem 2. Suppose the relative motion of the recruiter is a uniform circular motion, for any time t_0, there exists a critical relative motion's radius $R_{t'}$ in the time $t' \in [t_0, t_0 + T]$ satisfying Equ. (32). Then, within time $t_{\max}$, the final radius of the relative uniform circular motion R we design should satisfy the relationship $R \in \left[\sup\limits_{t' \in [t_0, t_0+T]} R_{t'}, \frac{v_1 t_{\max}}{2\pi}\right]$.

3.3 Optimization

In Section 3.1, we propose two patterns, including the 8-type and b-type. The best case for the 8-type is that the radius of the small circle is the minimum feasible value. To determine the optimal values of a and b in the 8-type, we must calculate the relative circular motion's minimum radius $R_{\min}$. We have previously proposed *Theorem 2*, which is suitable for the known relative speed v_1 but the unknown radius R. By using *Theorem 2*, we can fix the final parameter in the 8-type. And the b-type shown in Fig. 3 is just a schematic diagram. The final design should be optimized with the time cost index. In other words, we should make the trajectory the shorter, the better.

Consider a uniform relative motion with the speed v_1, and we can get a minimum radius of the relative circular motion $R_{\min}$ by *Theorem 2*. The degrees α and β represent the tangent directions of the *i*nitial point P_i and the *f*inal point P_f as shown in Fig. 4. Because there are some inherent parts in the b-type to transfer information, we need to optimize the red part in Fig. 4(a), making it shortest. So the optimization can be described as

$$\min_{\varphi(t)} \int_0^{t_F} \sqrt{\dot{x}_F^2(t) + \dot{y}_F^2(t)}\mathrm{d}t \tag{34}$$

$$\begin{aligned} \text{s.t.}\quad \dot{x}_F(t) &= v_1\cos\varphi(t) \\ \dot{y}_F(t) &= v_1\sin\varphi(t) \\ -\frac{v_1}{R_{\min}} &\le \dot{\varphi}(t) \le \frac{v_1}{R_{\min}} \\ x_F(0) &= x_{P_i} \\ y_F(0) &= y_{P_i} \\ \varphi(0) &= \alpha \\ x_F(t_F) &= x_{P_f} \\ y_F(t_F) &= y_{P_f} \\ \varphi(t_F) &= \beta \end{aligned}$$

where $\varphi(t)$ is the angle between the tangent vector of the trajectory and the x-axis, $x_F(t)$ and $y_F(t)$ are the relative motion displacements in the formation coordinate system, and t_F is the time cost in the process. The UAV's instantaneous state is determined by the triple $\langle x_F(t), y_F(t), \varphi(t)\rangle$.

For the optimization problem mentioned above, we can solve it with the help of existing conclusions. Dubins has proposed a solution to find the shortest smooth path from P_i to P_f, which starts with the direction α and ends with β [15]. The path curvature has the limitation at the same time. The fixed-wing UAVs motion model fits the characteristic of the Dubins model perfectly. Dubins set D includes six admissible paths $\{LSL, RSR, RSL, LSR, RLR, LRL\}$, where S stands for straight-line while L and R represent turning left and right.

Because the circle and straight line have special meanings in the b-type pattern, the trajectory we need to optimize is from P_i to P_f in Fig. 4(a). Establish a coordinate system as Fig. 4(a) shown, and we can get the coordinates and initial parameters. Regarding this situation as a long path case (circles defined by initial and final arc segments are non-intersection) at the search and rescue conditions, the shortest path must belong to RSL obviously.

The length of the Dubins curve is derived in [16]. By calculating each segment of the path, we can optimize our b-type trajectory as Fig. 4(b).

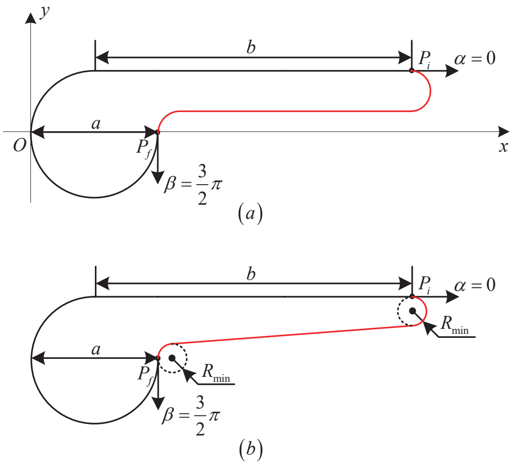

Fig. 4: Optimized b-type trajectory.

4 Simulation and Discussion

The strategy in this paper can be summarized as using the relative motion trajectory to transfer spatial information about the target. By using *Theorem 2*, two patterns, including the 8-type and b-type, are designed. Both of the two schemes use the characteristics of the figures themselves. For example, the proportional relationship represents the distance, and the axis direction expresses the direction. We optimize the design of patterns according to the time cost index. In addition to the theoretical explanation, two simulations are presented to demonstrate how the patterns perform under a common scenario.

4.1 Simulation

To discuss two patterns directly, we consider an ordinary situation as the target is 30 km away from the recruited at 30 degrees north of east while UAVs fly horizontally. The parameter in simulation can be found in Table 1. What needs to be explained is the distance d is between the target and the information transfer point. According to *Theorem 2*, we can calculate the minimum radius of relative circular motion $R_{min} = 0.0535$ km. Then, we can give out the design of patterns, as shown in Fig. 5 and Fig. 6. And $b/a = 3$. In order to distinguish the design of the two patterns, we denote a, b in (6) as a_8, b_8 in the 8-type and a_b, b_b in the b-type, respectively. Because the trajectory needs to have the minimum time cost, we let $a_8 = 2R_{min}$ and $a_b = 4R_{min}$ to avoid ambiguity in the b-type. Regardless of the direction of the target, the maximum widths of the two patterns are $8R_{\min}$ and $15R_{\min}$ respectively.

The actual flight trajectories of the recruiter are shown in Fig. 7. The blue solid line represents the recruiter's trajectory, and the red dots indicate the location of the recruited. The work in [14] describes a UAV energy consumption model. For fixed-wing UAVs with level flight under normal operations, their energy consumption follows as

$$E(\mathbf{q}(t)) = \int_0^T e(t)dt + \frac{1}{2}m\left(\|\mathbf{v}(t)\|^2 - \|\mathbf{v}(0)\|^2\right) \quad (35)$$

Table 1: Simulation parameter

Parameter	Value
Pre-set parameter c	10 km
Distance d	30 km
Target direction γ	30°
The recruited velocity v_0	0.05 km/s
The recruiter velocity v_1	0.02 km/s
The minimum turning radius r_{min}	0.12 km

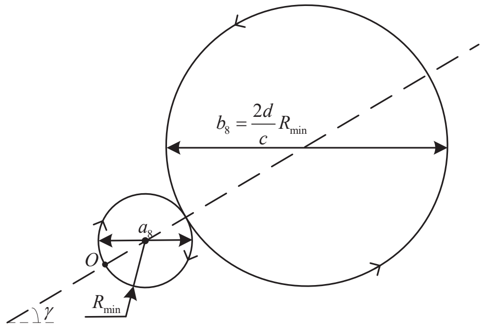

Fig. 5: The 8-type designed pattern.

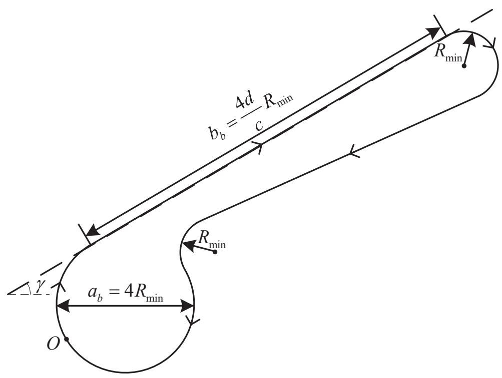

Fig. 6: The b-type designed pattern.

$$e(t) = c_1\|\mathbf{v}(t)\|^3 + \frac{c_2}{\|\mathbf{v}(t)\|}\left(1 + \frac{\|\mathbf{a}(t)\|^2 - \frac{\left(\mathbf{a}^{\mathrm{T}}(t)\mathbf{v}(t)\right)^2}{\|\mathbf{v}(t)\|^2}}{g^2}\right) \quad (36)$$

where $\mathbf{q}(t) \in \mathbb{R}^2$ is the trajectory, $\mathbf{v}(t) = \dot{\mathbf{q}}(t)$ is the velocity vector and $\mathbf{a}(t) = \ddot{\mathbf{q}}(t)$ is the acceleration vector. In addition, $c_1 = \frac{1}{2}\rho C_{D_0} S$, $c_2 = \frac{2W^2}{(\pi e_0 A_R)\rho}$, where ρ is the air density, the unit is $\mathrm{kg/m^3}$. And C_{D_0} is the zero-lift drag coefficient, S is a reference area, e_0 is the Oswald efficiency or wingspan efficiency, A_R is the aspect ratio of the wing. And the parameter c_1 and c_2 are assumed as 9.26×10^{-4} and 2250 [14]. The index performance is shown in Table 2.

Table 2: Index performance

Index \ Pattern	The 8-type	The b-type
Energy consumption (kJ)	3190.5	4604.2
time cost (s)	69	96

4.2 Discussion

The above results illustrate the performance of actual flight trajectories. After verification, the two patterns based

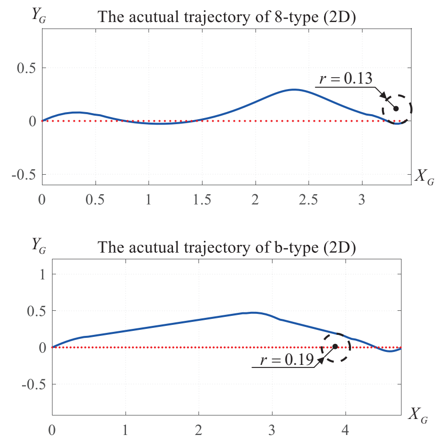

Fig. 7: The actual trajectory (2D).

on the design constraints we put forward meet the requirement of the minimum turning radius r_{min}.

For the time cost index, the 8-type needs less time than the b-type, which means the 8-type can complete the task faster. When it comes to the energy consumption part, the 8-type also consumes less energy than the b-type. Obviously, with the same information that needs to be transmitted, the 8-type is better than the b-type in terms of indexes. We test several times with the same direction but different distances and get the same conclusion. The reason is that the b-type's limitations make a_b is $4R_{min}$ in the shortest path scheme while the diameter a_8 is $2R_{min}$ in the 8-type.

However, the 8-type may have ambiguity in the process of recognizing graphics because of the similarity of the two circles. The recruited may have the probability of misjudging the information in some particular situation. So we must add the additional action to specify the starting point. For example, the pattern's flight can have several seconds of relative pause to declare the start point.

On the contrary, the b-type owns unique directivity and difference in graphic properties (the circle and the straight line), making the identification easier. But the distance from the position now to the target must be larger than $\frac{3+\sqrt{3}}{4}$ times the pre-set parameter c in the b-type. Fig. 8 below illustrates the extreme situation in the b-type.

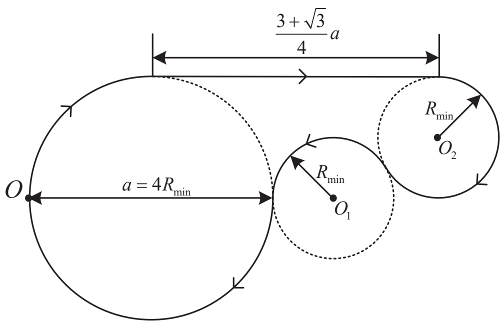

Fig. 8: The extreme situation in the b-type.

5 Conclusion

In this paper, the information transfer problem without direct communication is solved by a bio-inspired strategy. It is novel in that this strategy can share the message as the dance of bees while also avoiding direct communication. There are still some problems to be solved. Except for the minimum turning radius, other constraints of the fixed-wing UAVs are not considered. And the recruited is not necessary to fly at a constant speed, which means the constraint can be relaxed. Apart from these two typical patterns in spatial dimensions, we can consider encoding the temporal information into our strategy design.

Acknowledgment

This work is supported by Beijing Natural Science Foundation under Grant L182037 and the Aeronautics Power Foundation under Grant 6141B09050377.

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