FORMATION SHAPE CONTROL OF UNMANNED AIR VEHICLES

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Abstract

In recent years, mini size air planes called Micro Air Vehicle (MAV) attract lots of attention for the purpose of information gathering in the event of natural disaster, etc. The benefit of MAV is low cost, but its function is limited when it is used alone. Then, the use of multiple MAVs together as a flight formation is effective because it can integrate the function of each MAV to a multifunctional system as a group. Here, we are studying about the formation shape control in the flight formation of MAV. Previously, the feed forward control was used for this purpose, but it couldn't keep the desirable shape in any time. Then, we designed a new feedback control by using PID control, and applied it to the formation shape control. As a result, 80% of simulations could keep the desirable shape, but the formation split in other 20% simulations. The main reason of this split is the dropout of several MAVs at the border of the formation. We then investigated a new type interaction mechanism to solve this problem.

1 Introduction

In recent years, unmanned air vehicles have been studied vigorously for the purpose of information gathering [1]. Especially, we consider it effective to gather information in air over the disaster area such as the attacked site by the last earthquake in Japan. Conventional size airplanes, however, have several disadvantages such as a secondary disaster by crash, requirement of the runway for the take-off and landing, and the difficulty of using multiple airplanes because of a large cost. However, mini-size and light-weight airplanes called Micro Air Vehicle (MAV) (Fig. 1) have advantages over the conventional size airplanes because of the less dangerousness of secondary disaster, no need of runway for the take-off and landing, and the low cost which enables the operation of multiple airplanes.

This kind of mini-size air vehicle, however, has problems such as a limited function when it is used alone or a weakness to the air turbulence. One of the feasible solutions of these problems is to use multiple air vehicles as a group, namely flight formation of mini-size air vehicles. Using multiple MAVs at the same time can enhance the total function as a group even if the function of a single MAV is weak. It also can enhance the tolerance to the accident by replacing the disabled MAVs with normal MAVs in the same formation.

In this flight formation control, the change of formation shape is necessary to avoid obstacles or to operate the formation flight for various purposes. Then, in this study, we investigate the formation shape control focusing on the lateral expansion of formation shape and maintain the desirable shape stably for a long time.

Fig.1. MAV developed at Notre Dame University [2]

2 Flight formation control model

In this study, we base our flight formation control model on the motion of birds or fish group. These motions have been studied a lot in the past, focusing on the formation mechanism or the biological advantage [3, 4]. Referring to the results of these studies, we developed a flight formation control model as a combination of three simple motions, i.e. approach, parallel orientation, and repulsion. These motions are switched over according to the distance between the individual and its neighbor. To apply this switching rule to the flight formation control model, an interaction field is set around each MAV as shown in Fig.2. If the neighbor is away in the approach field, "approach" is selected and the MAV orients to the neighbor and approaches to it (Fig. 3(a)). If the neighbor is nearby in the repulsion field, "repulsion" is selected and the MAV moves away from the neighbor (Fig. 3(b)). If the neighbor is intermediate in the parallel orientation field, "parallel orientation" is selected and the MAV orients in parallel with the neighbor (Fig. 3(c)). When multiple MAVs fly together conducting this switching rule at the same time. flight formation of MAVs is realized [5].

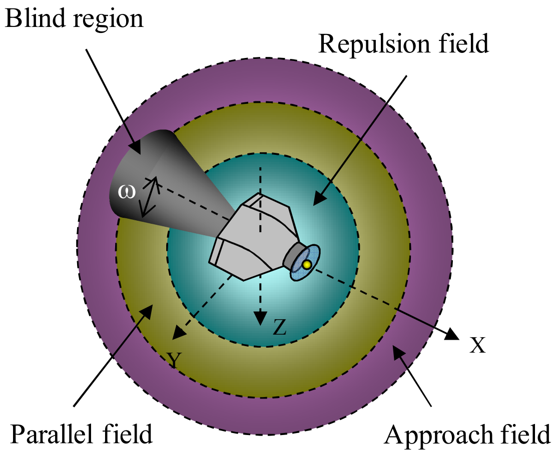
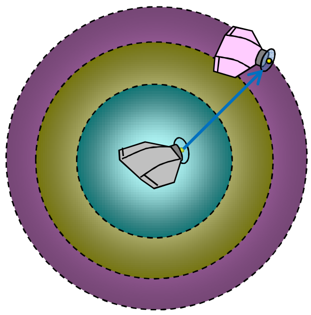
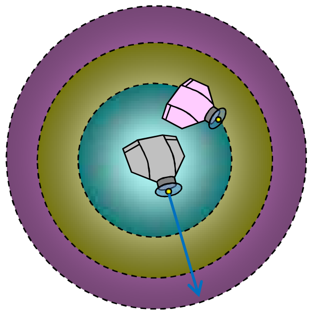


Fig.2. Interaction field


(a) Approach


(b) Repulsion

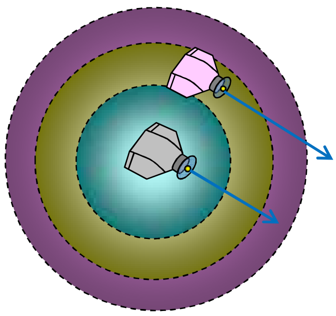

(c) Parallel orientation

Fig.3. Interaction rule

3 Formation shape control

In the previous study, we confirmed the similarity between the shape of interaction field and the formation shape [5]. A brief explanation of how this similarity occurs is as follows: in a stable flight condition, multiple neighbors distribute uniformly in the approach and parallel orientation field of MAV as shown in Fig.4. This is because the moving direction vectors for the neighbors in the approach field (red) orients radially and then they are cancelled, not inducing approach motion of MAV to any neighbors in the approach field. This prevents the MAV from turning right or left to approach the neighbor and makes it continue going forward. The moving direction vectors for the neighbors in the parallel orientation field (blue) orient forward and then they induce forward orientation of MAV, making a stable forward movement of MAV. When the position of MAV fluctuates right or left, or front or rear, the neighbors in each direction enter into the repulsion field, which induces the MAV to return to the original position. Therefore, this situation is considered stable.

By using this nature, we can change the position of neighbors in the interaction field by changing the shape of the interaction field as shown in Figs. 5(a) and 5(b), and when all MAVs change its interaction field shape into the shame shape, this redistribution of neighbors in the interaction field of all MAVs unites together, resulting in the change of formation shape in a similar shape of the interaction field of each MAV. As a result, we can control the formation shape by changing the shape of interaction field of each MAV.

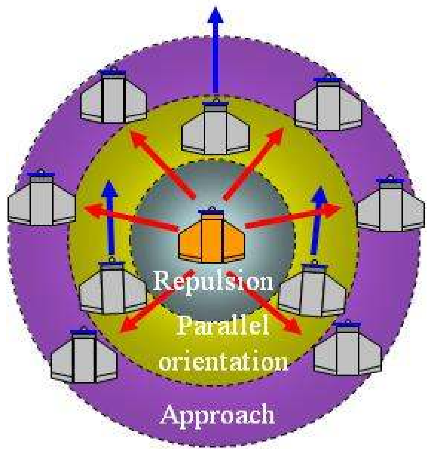
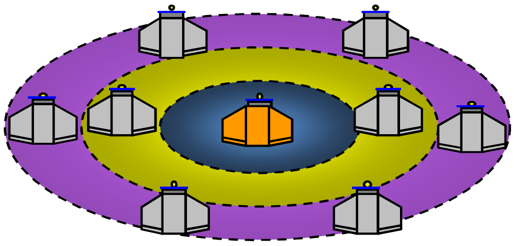
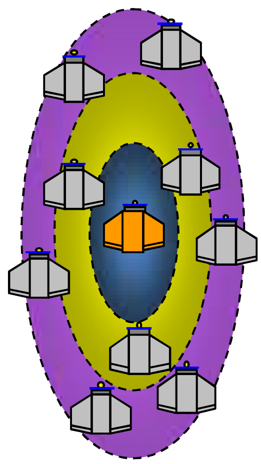


Fig.4. Stable state



(a) Lateral expansion of interaction field



(b) Longitudinal expansion of interaction field

Fig. 5. Change of the shape of interaction field and the position of neighbors in the interaction field

4 Formation shape control using feedback control

4.1 Conventional method

In the previous study [5], we used a feed forward control for formation shape control. For example, we expanded the formation shape in a particular direction by expanding the interaction field in the same direction. However, this method had a problem that it was difficult to keep the same formation shape stably. This was because the lack of correction mechanism when the formation shape deviates from the specified shape. We then need the feedback control as the correction mechanism of formation shape deviation.

4.2 Formation shape control using PID control

We then designed a new feedback control system by using PID control. Fig. 6 shows the block diagram of feedback control. The output of PID controller $r_y(t)$ in Fig. 6, which is the lateral expansion ratio of interaction field, is calculated by using the following equation:

$$r_y(t) = C_P(e(t) + \frac{1}{C_I}\int_0^t e(t)dt + C_D\frac{de(t)}{dt}) \quad (1)$$

where $e(t)$ is the deviation of system output $E(t)$ (current expansion) from the target value of expansion E_T, i.e. $e(t)=E(t)-E_T$, C_P is the proportional gain, C_I is the integral time, and C_D is the derivative time. The values of C_P, C_I, C_D are calculated by using the ultimate sensitivity method [6]. In the ultimate sensitivity method, the limit gain K_u is defined as the value of C_P when the system output keeps stable vibration with the constant amplitude and the constant

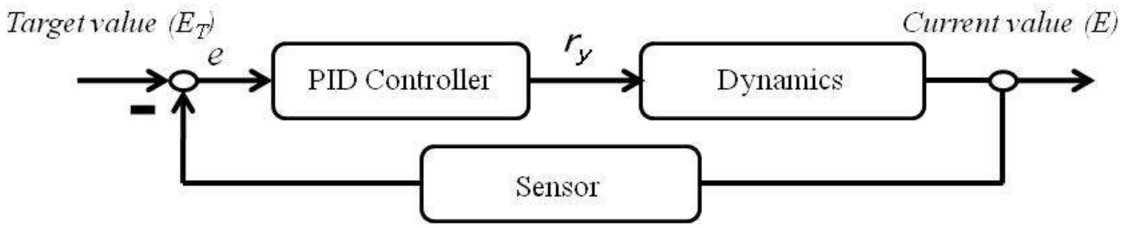


Fig.6. Block diagram of feedback control system

Table 1. Determination of controller parameter by the ultimate sensitivity method

Controller	C_P	C_I	C_D
P	0.5Ku		
PI	0.45Ku	Pu/1.2	
PID	0.6Ku	0.5Pu	Pu/8

frequency P_u. At this stable vibration state, C_I and C_D take the maximum and zero value, respectively. With these two parameters K_u and P_u, the values of C_P, C_I, C_D are determined by using Table 1.

4.3 Simulation of formation shape control

In the simulation, 50 MAVs are used each of which has the specification as shown in Table 2. The parameters for interaction, e.g. the radius of interaction field or the maximum number of interacting neighbors, used in the calculation is shown in Table 3, where BL denotes the body length of MAV (1BL=0.33m). 10 calculations are conducted with the different turbulence conditions. Turbulence is added to the moving direction of each MAV by using the random function which generates the series of random values based on the random seed. We used 10 different random seed (1, 2, …, 10) for 10 calculations. The initial condition, i.e. initial position, speed, and moving direction of 50 MAVs, is same for all 10 calculations.

We conducted the lateral expansion of formation shape. Target value of expansion is 10 times of the initial lateral length of formation. By using the similarity between the formation shape and the shape of interaction field, we expanded the shape of interaction field laterally by using the lateral expansion ratio $r_y(t)$ determined by Eq. (1) in the formation shape control.

5 Results

5.1 Determination of PID control parameters

PID control parameters in Eq. (1) and Table 1 are given by using the ultimate sensitivity method as follows:

ultimate gain, *Ku*	$1.35*10^{-5}$
ultimate period, *Pu*	23[sec]
proportional gain, C_P	$8.1*10^{-6}$
integral time, C_I	11.5
derivative time, C_D	2.875

5.2 Results of simulation

Fig. 7 shows the simulated flight formation. Figs. 8(a) and 8(b) show the calculated value of lateral expansion of successful calculations and unsuccessful calculations, respectively. Each line of these figures shows the result of calculation with the specified seed value (seed*). Red line shows the target value (10 times of initial expansion). According to Fig. 8(a), 8 cases out of 10 cases converged to the target value until about 800 steps although fluctuations were observed, where one step has 0.1sec time interval, so 800 steps mean 80 sec. These 8 cases were considered successful because they could keep convergence to the target value for about 80sec although several cases showed sudden increase after 800 steps. In Fig. 8(b), however, other 2 cases couldn't converge to the target value and began to increase continuously after 100 or 200 steps (10 sec or 20sec, respectively). These two cases were then considered unsuccessful. These continuous increases were caused by the split of formation into several sub-groups. The divergences of several cases after 800 steps in Fig. 8 were also caused by the split of formation. These splits were typically caused by the drop out of several MAVs at the boarder of the formation or by the sudden turning motion of formation.

5.3 Results of calculation with large approach field

As stated in the previous section, one of the reasons for the split of formation is the drop out of MAVs at the boarder of the formation. MAVs flying at the boarder of the formation are subject to lose sight of other MAVs because the neighbors in the interaction field of MAVs at the boarder are not distributed widely in the interaction field but exist in the limited area of the field. Therefore, the MAVs at the boarder easily lose sight of their neighbors when they are separated from the formation because of the air turbulence, etc. The divergence of case 6 in Fig. 8(b) (seed 6) was caused by this dropping out of several MAVs at the boarder of the formation.

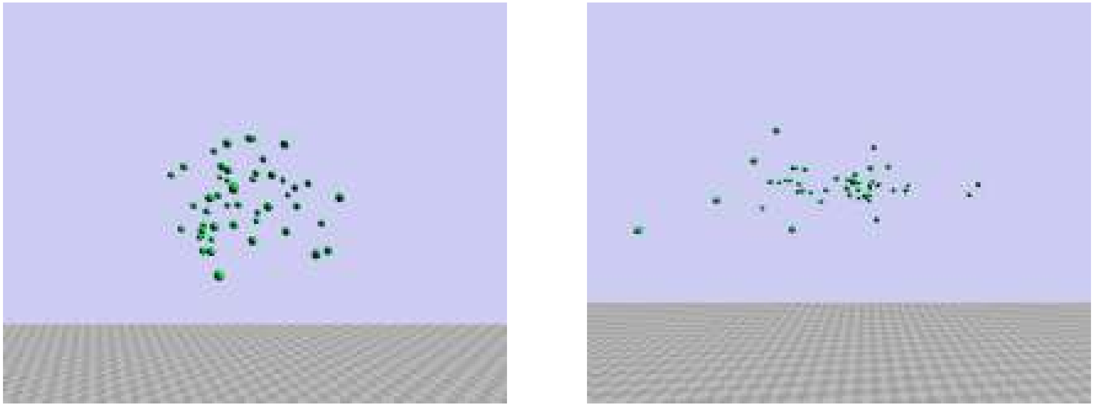
The solution of this problem is to have a large approach field to sense the distant neighbor. We then increased the radius of approach field to 1.7 times (=33BL) of the original value while other parameters were left unchanged, and conducted the simulation with seed value 6. Fig. 9 shows the result of this calculation. The lateral expansion did not show the divergence but converged to the target value. However, this increase of radius of approach field did not have the same effect on other diverged cases. We need other countermeasure to realize fully stable formation shape control.

Table. 2. Specifications of MAV

Wing		
	Area (m^2)	0.135
	Span (m)	0.6
	Mean aerodynamic chord length (m)	0.2
	Aerodynamic center position (mac)	0.25
	Aspect ratio	2.667
	Effective aspect ratio	2.133
	Taper ratio	1
	Sweepback angle (deg)	0
	Dihedral angle (deg)	10
	Lift slope	3.243
Horizontal tail		
	Area (m^2)	0.02
	Span (m)	0.2
	Aspect ratio	2
	Effective aspect ratio	1.6
	Sweepback angle (deg)	0
	Lift slope	2.793
	Horizontal tail position (m)	0.45
	Horizontal tail volume (m^3)	0.333
Vertical tail		
	Area (m^2)	0.01
	Span (m)	0.1
	Aspect ratio	1.55
	Effective aspect ratio	1.24
	Sweepback angle (deg)	0
	Lift slope	2.405
	Vertical tail position (m)	0.45
	Distance from X-axis to aerodynamic center (m)	0.05
	Vertical tail volume (m^3)	0.056
Fuselage		
	Volume (m^3)	0.0004
	Length, BL (m)	0.33
	Weight (kgf)	0.27
	Moment of inertia (m^2kg)	
	I_{xx}	0.011
	I_{yy}	0.013
	I_{zz}	0.007
	Product of inertia I_{xz}	0.0006
Total		
	Position of center of gravity (mac)	0.15
	Drag coefficient	0.1

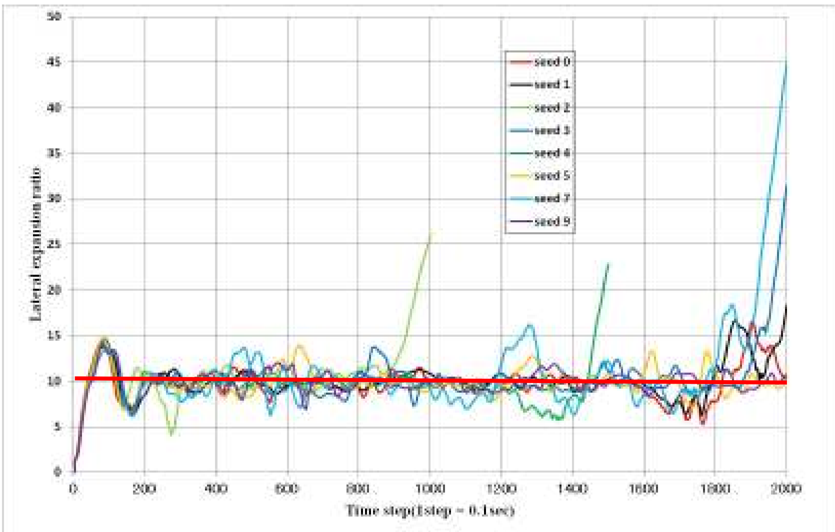
Table. 3. Interaction parameters

Radius of repusion field, R_r (BL)	5
Radius of parallel orientation field, R_p (BL)	25
Radius of approach field, R_a (BL)	30
Blind-region angle, ω (deg)	30
Maximum number of interacting neighbors	4

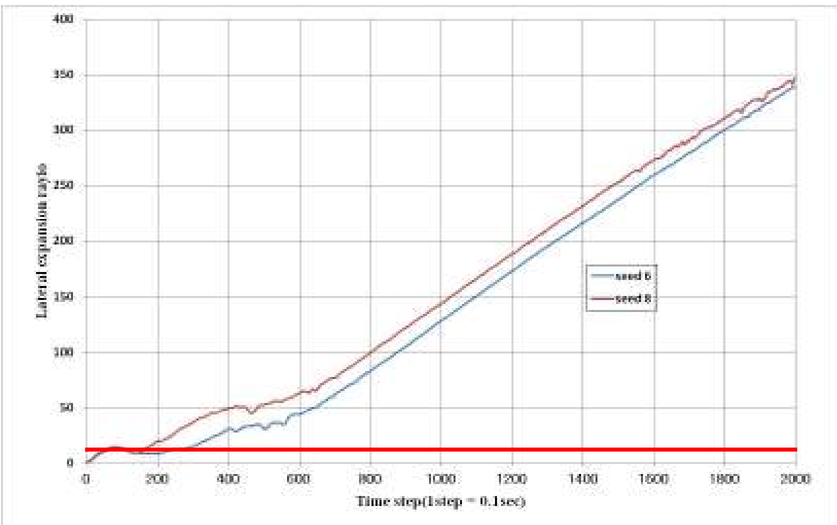


(a) Initial stage (b) Laterally expanded formation

Fig. 7. Simulated flight formation



(a) Successful calculations



(b) Unsuccessful calculations

Fig. 8. Lateral expansion ratio of flight formation

6 Conclusion

In this study, a newly designed PID control was applied to the formation shape control of multiple MAVs. We conducted the lateral expansion of formation shape and confirmed that the shape could converged to the target value in 8 cases out of 10 cases, showing the better performance than the previous conventional feed-forward control system. However, in the remaining 2 cases, the expansion diverged because of the split of formation. The reason for this split was considered that the MAVs at the boarder of the formation lost sight of other MAVs and dropped out from the formation. We then increased the size of approach field and could get successful conversion of school shape for one case (seed 6). For other several cases, however, this increase of radius of the approach field did not have desirable effect. We then need other countermeasures to realize fully stable formation shape control.

We are now investigating the improvement of the interaction mechanism among MAVs. Current interaction model uses three interaction fields, approach, parallel orientation, and repulsion fields, and these three fields change discontinuously from one field to another field. This causes the motion of MAV to change discontinuously from one motion to another motion, e.g. from approach to parallel orientation according to the distance of neighbor as shown in Fig. 3. This might cause the harmful effect on the stability of formation shape control. We are now developing new interaction mechanism to get rid of this discontinuity, and would test its feasibility in near future.

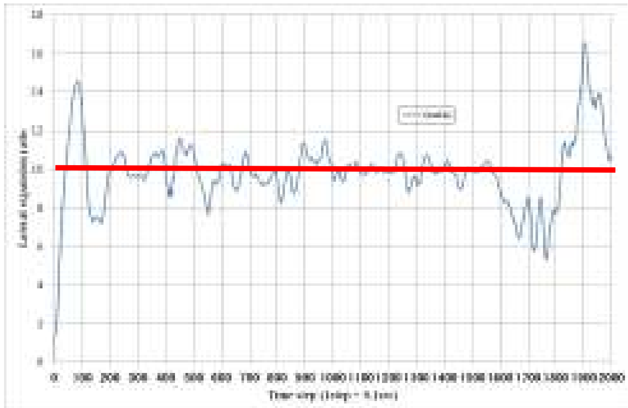


Fig. 9. Lateral expansion ratio of seed 6 with the increased radius of approach field.

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