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IT Convergence UAV Swarm Control for Aerial Advertising

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공중 광고를 위한 IT 융합 무인항공기 군집 제어

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Abstract As the price of small UAVs is getting cheaper and its controllability is getting greatly increased, many aerial applications using both fixed-wing and hoverable UAVs have appeared in recent years. In this paper, a new aerial advertising method is proposed using four hoverable UAVs. Using the UAV swarm control method, four UAVs are maneuvered to carry a 7.07 × 7.07 m^2 square banner along collision-free and predefined waypoints for aerial advertising. According to simulation results, it takes about 270 s for UAVs to perform aerial advertising in 669 × 669 m^2 size area and the minimum distance among UAVs turns out to be 0.45 m which proves there is no any collision. Due to abrupt direction changes of UAVs along the predefined waypoints, UAVs cannot always maintain exact square formation and it results the maximum and minimum side lengths of square formation to be 10.35 m and 1.96 m, respectively. Also, the maximum and minimum diagonal lengths of square formation turn out to be 14.75 m and 2.78 m, respectively.

- **Key Words** : Aerial Advertising, GA, mTSP, Swarm, UAV

요 약 소형 무인항공기의 가격이 저렴해지고 제어가 쉬워짐에 따라, 고정익 또는 회전익 무인항공기를 사용하는 항공 어플리케이션이 최근 많이 등장하였다. 본 논문에서는 4대의 회전익 무인항공기를 사용한 새로운 공중 광고법이 제안되었다. 무인항공기 군집 제어를 통해, 4대의 무인항공기가 7.07 × 7.07 m^2 사이즈의 정사각형 현수막을 사전에 정의된 비행경로를 따라 운반하며 공중 광고를 한다. 시뮬레이션 결과에 따르면, 무인항공기들이 669 × 669 m^2 크기의 영역에서 전체를 비행하며 공중 광고를 수행하는 데는 총 270 s 가 소요되며, 무인항공기들 사이의 최소 거리는 0.45 m 로서 충돌이 발생하지 않음이 밝혀졌다. 몇몇 급격한 방향 전환이 필요한 경로로 인하여 무인항공기들이 정확한 정사각형 군집 비행을 수행하기 어려운 구간이 있으며, 이때 정사각형 편대 비행의 최대 및 최소 변의 길이는 10.35 m와 1.96 m로 밝혀졌다. 또한, 정사각형 편대 비행의 최대 및 최소 대각선 길이는 각각 14.75 m와 2.78 m로 파악되었다.

- **주제어** : 공중 광고, 유전연산법, 다중 외판원 여행 문제, 군집, 무인항공기

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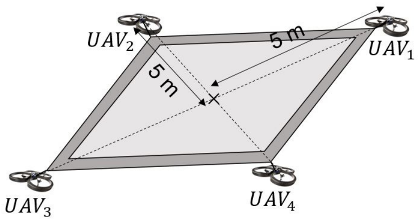
1. Introduction

As time goes by, the cost of an unmanned aerial vehicle (UAV) is getting cheaper and so UAVs are no longer belongings of only researchers but for everyone. Applications where a UAV is used are tremendously increased since a UAV can fly around anywhere by avoiding almost every object in 3D space [1,2,3,4].

Particularly in this paper, a swarm of UAVs is maneuvered to carry a wide square banner or a flexible paper screen for aerial advertising as shown in Fig. 1. Total four UAVs are manipulated to carry a banner with as less banding or tilting as possible so that people could clearly watch the banner from the ground.

No companies or governments have tried this kind of advertising yet, though there is traditional advertising using a fixed-wing airplane [5]. Advertising creative including the aerial advertising using a swarm of hoverable UAVs is already a worldwide trend and there are countless number of exotic and effective advertising examples and related studies [6,7].



[Fig. 1] Four hoverable UAVs carrying a square banner

Today, a UAV needs two or more pilots to control and perform missions (filming, picturing, and etc.) at the same time. Cooperative missions involving many UAVs are difficult because of the great number of constraints that have to be respected for safety and reliable performance. The great difficulty of the problem of autonomy is because of unstructured environment and uncertainties in sensing and actuation.

There are numerous number of dynamic models for UAVs flight simulations [8,9] and point-mass aircraft models interchangeably applicable both to fixed-wing and hoverable UAVs are adopted for this paper [10]. In [10], a UAV (=chaser) can track pre-defined waypoints (=prey) and similar methods are also attempted by other researchers [11,12,13].

In this paper, scalable methods are developed by which four hoverable UAVs can cooperatively track collision-free and predefined waypoints by maintaining a square swarm formation carrying a 7.07 × 7.07 m^2 size banner for the aerial advertising purpose. This swarm formation control of UAVs has been a hot topic among UAV researchers [14,15,16].

The flow of this paper is as follows. Section 2 explains the UAV governance models including prey model, chaser model, tracking model, and swam model. Section 3 shows Simulink design of the governance models and Section 4 shows corresponding simulation results. Section 5 finally proposes the conclusion of this paper and future works.

2. Governance Model

The governance models from [10] are adopted for this paper. These models are quite realistic in the sense that it counts time delays, including communication delay between the ground station and UAV and computation delay required for the assigned mission performance. Overall governance models are divided into four parts; a prey model, a chaser model, and a tracking model with which a chaser UAV flies along the path which a prey left on the ground; swarm model with which UAVs fly by maintaining a square shape formation.

2.1 Prey Model

The position of the prey is defined as

$$\begin{aligned} P_{p,k} &= P_{p,k-1} + TV_{p,k-1}, \\ V_{p,k} &= V_{p,k-1} + TA_{p,k-1}, \end{aligned} \quad (1)$$

where P_p is the prey position vector ($[p_{x,p}, p_{y,p}]$, m), V_p is the prey velocity vector ($[v_{x,p}, v_{y,p}]$, m/s), A_p is the prey acceleration vector ($[a_{x,p}, a_{y,p}]$, m/s^2), T is the sampling time (s), and k is the given step time. Here, all vectors contain only x and y plane motion since the prey can only move on the ground.

2.2 Chaser Model

The position of the chaser considers two more factors compared to the generic UAV models including a position tracking time constant, τ_x, and a velocity tracking time constant, τ_v, as

$$\begin{aligned} P_{c,k} &= P_{c,k-1} + TV_{c,k-1}, \\ V_{c,k} &= -\frac{T}{\tau_x \tau_v} P_{c,k-1} + \left(1 - \frac{T}{\tau_v}\right) P_{c,k-1} + \frac{T}{\tau_x \tau_v} P_{p,k-1}, \end{aligned} \tag{2}$$

where P_c is the chaser position vector ($[p_{x,c}, p_{y,c}, p_{z,c}]$, m) and V_c is the chaser velocity vector ($[v_{x,c}, v_{y,c}, v_{z,c}]$, m/s).

2.3 Tracking Model

The tracking model governing the quarry of a chaser tracking a prey is defined in explicit discrete time-invariant state-space model representation as,

$$\begin{bmatrix} \hat{P}_p \\ \hat{V}_p \end{bmatrix}_k = \begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^m \begin{bmatrix} \hat{P}_p \\ \hat{V}_p \end{bmatrix}_{k-m} + \sum_{i=1}^{m-1} \begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^i \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ T & 0 \\ 0 & T \end{bmatrix} \hat{A}_{p,k} \tag{3}$$

where symbol ^ represents an estimator, $m=5$, $\hat{P}_{p,k} = P_{p,k-1} + \nu_1$ (m), $\hat{V}_{p,k} = V_{p,k-1} + \nu_2$ (m/s),, $\hat{A}_{p,k} = \frac{1}{T}\sum_{i=1}^{m} c_i \left(V_{k-i+1} - V_{k-i} \right)$ (m/s^2), $\sum_{i=1}^{m} c_i = 1$, $c_1 = \frac{17}{35}$, $c_2 = \frac{1}{4}$, $c_3 = \frac{1}{8}$, $c_4 = \frac{1}{16}$, and $c_5 = \frac{1}{32}$.

2.4 Swarm Model

The swarm model for maneuvering four UAVs is designed as,

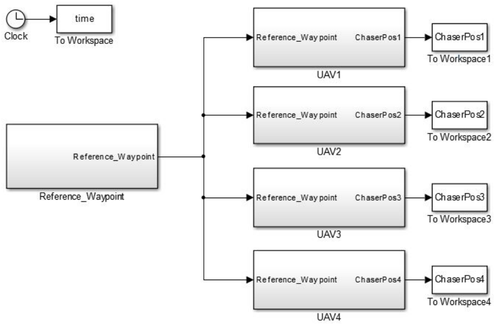
$$\hat{P}_{UAV_i} = \hat{P}_c + rR(\psi_h)R(\psi_i)\frac{\hat{P}_c - P_{ave}}{\left|\hat{P}_c - P_{ave}\right|}, \tag{4}$$

where P_{UAV_i} is the position of the ith UAV ($[p_{x,uav_i}, p_{y,uav_i}, p_{z,uav_i}]$, m), r is the distance between the center and corner of the square advertising banner (m), R is the rotation matrix, ψ_h is the heading direction angle of P_{ave} (rad), $\psi_i = \frac{2\pi}{m}(i-1)$ (rad), $m=4$, $i \in \{1, \ldots, m\}$, and $P_{ave} = \frac{1}{m}\sum_{i=1}^{m} P_{UAV_i}$ ($[p_{x,ave}, p_{y,ave}, p_{z,ave}]$, m).

3. Simulink Design

Simulink, a graphical programming environment, is one of the widely used graphical block diagramming tools and is heavily used in the aerospace industry for the flight dynamics simulations [17,18].

Overall Simulink design is shown in [Fig. 2]. Each UAV is independently controlled to follow a personalized and predefined waypoints assigned by a Reference_Waypoint block.



[Fig. 2] Overall Simulink design

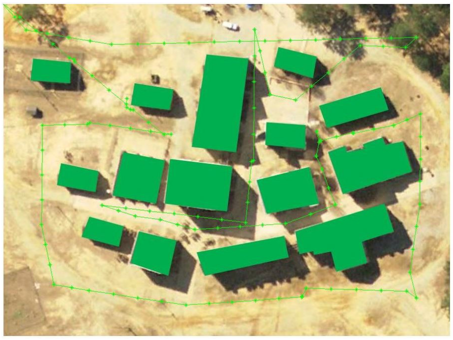
4. Simulation Result

All simulations are performed with hoverable type UAVs having initial system properties;
$P_{uav,1} = P_{uav,2} = P_{uav,3} = P_{uav,4} = [0, 669, 0]\,m$,
$v_{uav} = [0, 0, 0]\,m/s$, $a_{uav} = [0, 0, 0]\,m/s^2$,
$\theta_{uav} = [0, 0, 0]\,rad$, $w_{uav} = [0, 0, 0]\,rad/s$,
$Altitude_{\min} = 25m$, $Altitude_{\max} = 30m$,

$\| v_{uav,\min} \|_2 = 0 m/s$, $\| v_{uav,\max} \|_2 = 20 m/s$,
$\| a_{uav,\min} \|_2 = 0 m/s$, $\| a_{uav,\max} \|_2 = 10 m/s$,
$\tau_{pos} = 0.25 s$, $\tau_{vel} = 0.5 s$, and $t_{step} = 0.01 s$.

A laptop used for simulations has the following system properties; Intel(R) Core(TM) i7-4650U CPU @ 2.30 GHz processor, 64-bit operating system, and 8.00 GB RAM.

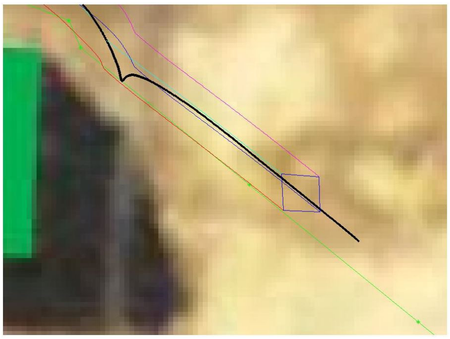
UAVs follow predefined, collision-free, and time optimal waypoints which are generated by using the genetic algorithm (GA) based multiple traveling salesman problems (mTSP) algorithm [19]. Waypoints are drawn in green as shown in [Fig. 3].



[Fig. 3] Predefined waypoints

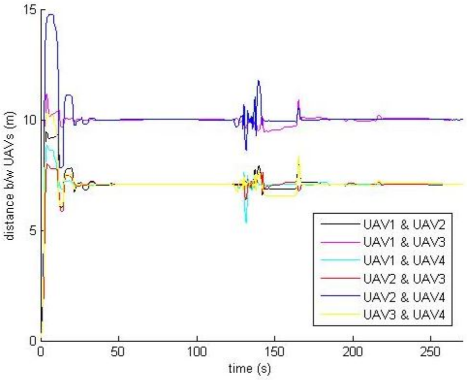
After simulations, flight traces of UAVs are shown in four different colors ([Fig. 4] and [Fig. 5]). Here, a black line represents reference waypoints which are generated by considering system dynamic properties of UAVs and with which UAVs are able to seamlessly follow. In [Fig. 5], a blue square represents a square banner which four UAVs carry.

[Fig. 4] Flight traces of four UAVs



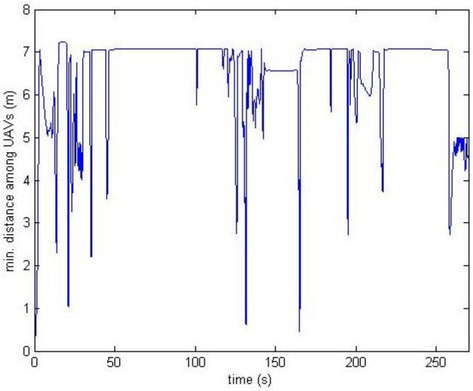
[Fig. 5] Close look of UAV flight traces

[Fig. 6] shows distances between each pair of UAVs. Most of the time, four UAVs form a square having a side length of 7.07 *m* and a diagonal length of 10 *m* except three sections; 0-36 *s*; 123-145 *s*; 164-168 *s*. These are the moments when abrupt flight direction change occurs and indicated in [Fig. 4].



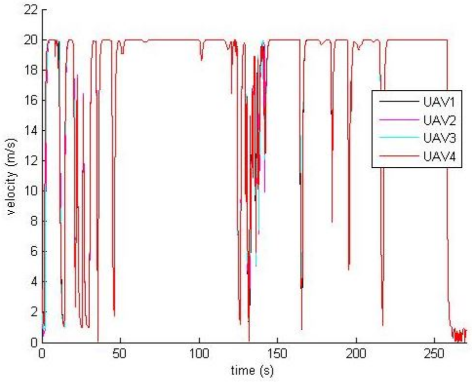
[Fig. 6] Distances between each pair of UAVs

[Fig. 7] shows the minimum distance among UAVs and it is clearly shown that none of any collision is occurred. Most of the time, the minimum distance maintains about 7.07 *m*. which is the side length of the square.



[Fig. 7] Minimum distance among UAVs

As we expected, velocities of UAVs are controlled well to be between the minimum velocity, 0 *m/s*, and the maximum velocity, 20 *m/s* as shown in [Fig. 8]



[Fig. 8] Velocities of UAVs

Finally, the overall simulation result is summarized in <Table 1>.

<Table 1> Summary of simulation result

Simulation Time	270 *s*
Min. Distance between UAVs	0.45 *m*
Max. Velocity of UAVs	0.04 *m/s*
Min. Velocity of UAVs	20.00 *m/s*
Max. Side Length of Square	10.35 *m*
Min. Side Length of Square	1.96 *m*
Max. Diagonal Length of Square	14.75 *m*
Min. Diagonal Length of Square	2.78 *m*

5. Conclusion

A cooperative mission planning using four hoverable UAVs carrying a square banner for aerial advertising is performed and shown to be applicable to real-life based on simulation results. This kind of new aerial advertising using UAVs will certainly bring a positive effect on the advertising industries. In the future, experiments using four hoverable UAVs will be performed and experiment results will be compared with simulation results.

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