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Air-ground cooperative exploration of 3D complex environment with maximized visibility and obstacles avoidance

YuXuan Wu
College of Information Science and Technology
Beijing University of Chemical Technology
Beijing, China
2019200764@mail.buct.edu.cn

Jing Wang*
School of Electrical and Control Engineering
North China University of Technology
Beijing, China
jwang@ncut.edu.cn

Meng Zhou
School of Electrical and Control Engineering
North China University of Technology
Beijing, China
zhoumeng@ncut.edu.cn

Zhe Dong
School of Electrical and Control Engineering
North China University of Technology
Beijing, China
dongzhe@ncut.edu.cn

YangQuan Chen
Mechatronics,Embedded Systems and Automation Lab
University of California, Merced
CA 95343, USA
ychen53@ucmerced.edu

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***Abstract*—Unmanned aerial vehicles (UAVs) can provide vision at high altitude. In this paper, multi-UAVs and ground vehicle are utilized to explore a complex environment with obstacles. The desired UAV formation is proposed around ground vehicle to provide wider vision. The Interfered Fluid Dynamical System (IFDS) method is utilized to guide UAVs avoid obstacles, while the desired formation need be maintained. Then formation control scheme of multi-UAVs is updated to combine with IFDS method according to original formation and obstacles avoidance. Simulation results shows that multi-UAVs can avoid obstacles and maintain the desired formation around ground vehicle during exploration.**

***Index Terms*—Mult-UAVs, Formation control, Obstacles avoidance, Air-ground collaboration**

I. Introduction

Unmanned vehicles have been developed rapidly. The UAVs got many advanced advantages such as high concealment and mobility [1], [2]. Complex missions such as environmental exploration [3], surveillance [4] and target tracking [5] can be performed with the help of UAVs to provide vision safely [6].

Many efforts are proposed to track moving target using multi-UAVs [7], [8]. In order to coordinate multi-UAVs, communication capabilities such as sensing ability or topological interactions [9], [10] need be promised. Besides, the information fusion method is utilized to process the information and communication noise [11], [12].

UAVs can also cooperate with ground unit [13]. By using a probabilistic path planning method, UAVs and ground vehicle are utilized to track target in urban environment [14], [15]. In environmental exploration, UAVs need track ground unit and provide vision in the desired formation, while many efforts are proposed to solve this problem using multi-UAVs [16]–[18].

The obstacle avoidance method must be utilized for UAVs when exploring the complex environment. The obstacles avoidance method is combined with the formation control scheme [19], [20]. The model predictive formation control is utilized to guide UAVs avoid collision [22]. The current obstacles avoidance method can be divided into several types: heuristic search based method, optimization algorithm [21], potential field and stream function based method. To promise the computational efficiency and quality of trajectory in 3D complex environment, an IFDS based method is utilized to guide UAV avoid obstacles smoothly [23], [24]. The IFDS method will not change the stability and general direction of original system, so it is suitable to combined with formation scheme of multi-UAVs.

Multi-UAVs and ground vehicle are utilized to explore a complex environment with obstacles. The UAVs are responsible to provide wider vision for ground vehicle. The detection sensor is mounted on UAV, however the coverage area of

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sensor is limited. Then multi-UAVs can form the desired formation around ground vehicle cooperatively to maximizes the total vision area of UAV formation.

The desired formation requires UAVs to be evenly distributed around ground vehicle. The flying height and radial distance from vehicle to UAV are designed under constraints to maximizes the total vision area. The main goal is to let multi-UAVs track the ground vehicle in desired formation and avoid obstacles at same time. Overall, the main contributions can be divided into several parts as follow:

1) The desired UAV formation is proposed to maximizes the total vision area in simple environment. The desired flying height and radial distance are optimized under constraints.
2) The formation control scheme of multi-UAVs is combined with IFDS method when exploring the complex environment. It is updated according to original desired formation and risk of collision.
3) The simulation is finished with three UAVs and ground vehicle. The results showed that multi-UAVs can maintain the desired formation around ground vehicle and avoid obstacles at same time in complex environment.

The rest of this paper is organized as follows. Section 2 gives the mathematical model of UAVs and ground vehicle. Section 3 gives the desired UAV formation and updated control scheme of multi-UAVs in complex environment. In section 4, the simulation verify the effectiveness of proposed method to guide UAVs avoid collision and maintain the desired formation in complex environment. Lastly, conclusion is given in section 5.

II. Mathematical formulation

Mathematical model of UAVs and detection sensor are described in this section. The model of ground vehicle is also described, respectively.

A. Model of UAV

Several homogeneous quadcopters are utilized in this mission, shown in Fig.1. The mathematical model of quadcopter is given as,

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{z}_i \end{bmatrix} = \begin{bmatrix} \cos\psi_i\cos\theta_i & -\sin\psi_i\cos\phi_i + \cos\psi_i\sin\theta_i\sin\phi_i & \sin\psi_i\sin\phi_i + \cos\psi_i\sin\theta_i\cos\phi_i \\ \sin\psi_i\cos\theta_i & \cos\psi_i\cos\phi_i + \sin\psi_i\sin\theta_i\sin\phi_i & -\cos\psi_i\sin\phi_i + \sin\psi_i\sin\theta_i\cos\phi_i \\ -\sin\theta_i & \cos\theta_i\sin\phi_i & \cos\theta_i\cos\phi_i \end{bmatrix} \begin{bmatrix} w_{x,i} \\ w_{y,i} \\ w_{z,i} \end{bmatrix} \tag{1}$$

where $P_i = (x_i, y_i, z_i)$ is position of ith quadcopter based on ground system, (i=1,...,n). w_i is velocity vector based on vehicle coordinate system, and ϕ_i, θ_i, ψ_i are roll, pitch and yaw angle of ith quadcopter. The flight control system of UAVs are assumed to be stable, then the desired velocity, altitude of UAV can be well tracked.

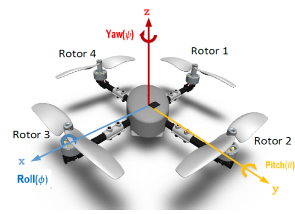


Fig. 1. Basic structure of quadcopter

B. Model of detection sensor

The detection sensor with adjustable observation angle is mounted on UAV to provide vision. The coverage area of sensor represent the field of view (FOV) of UAV, shown in Fig.2. The radius r of the FOV is given as,

$$r = h\tan\gamma \tag{2}$$

where h is flying height of UAV and γ is the maximum sensor field angle. Then the area is expressed as,

$$S_{FOV} = \{(x_s, y_s) \in R^2 | (x_s - x_{os})^2 + (y_s - y_{os})^2 \le r^2\} \tag{3}$$

Location (x_s, y_s) is inside the area S_{FOV}. The center (x_{os}, y_{os}) coincide with the location (x_i, y_i).

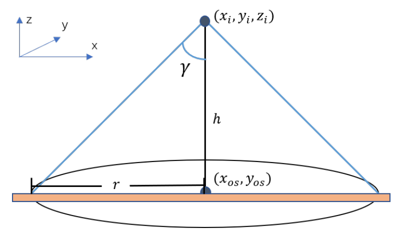


Fig. 2. Coverage area of detection sensor

C. Model of ground vehicle

The state vector $X_G(k)$ and mathematical model of ground vehicle are given as,

$$\begin{aligned} &X_G(k) = (x_G(k), x_G{'}(k), x_G{''}(k), y_G(k), y_G{'}(k), y_G{''}(k))^T \\ &X_G(k+1) = GX_G(k) + q(k) \end{aligned} \tag{4}$$

where $q(k)$ is a Gauusian process noise which satisfy $p(q) \sim N(0, \eta)$, and η is covariance matrix. G is transition matrix.

III. Formation control of multi-UAVs and obstacles avoidance

The desired UAV formation around ground vehicle is proposed to maximizes the total vision area, where the desired flying height and radial distance are designed under constraints.

In simple environment, the formation control scheme is proposed to let multi-UAVs form the desired UAV formation, while the scheme is updated in complex environment to combine with IFDS method.

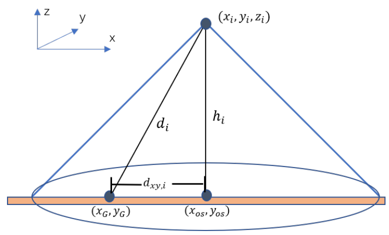


Fig. 3. Distance between UAV and ground vehicle

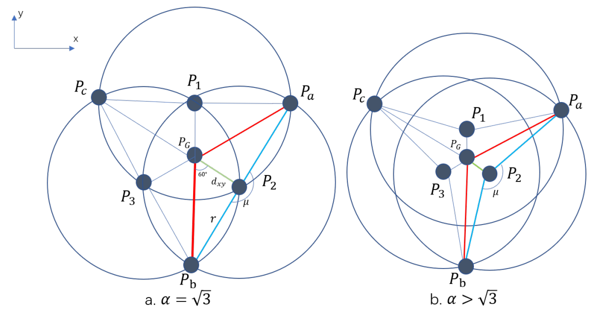


Fig. 4. Total vision areas S_{total} of UAV formation with different α

A. Optimal formation in simple environment

In the air-ground cooperative exploration, the ground vehicle is responsible for the communication. Then the desired UAV formation must be obtained under the distance constraints between UAV and vehicle for stable communication.

The flying height h_i of ith UAV and radial distance $d_{xy,i}$ between UAV and ground vehicle (x_G, y_G) on xy plane are shown in Fig.3. The $d_{xy,i}$ is given as,

$$d_{xy,i} = ((x_G - x_i)^2 + (y_G - y_i)^2)^{\frac{1}{2}} \tag{5}$$

The distance d_i between ith UAV and ground vehicle P_G is constrained for stable communication. The d_i is given as,

$$\begin{aligned} & d_i = (d_{xy,i}^2 + h_i^2)^{\frac{1}{2}} \\ & d_i \leq d_{\max}/\lambda \end{aligned} \tag{6}$$

where $d_{\max}$ is the distance constraint. The dilatation coefficient λ greater than 1 is introduced here.

To maximizes the total vision areas S_{total}, UAVs need be distributed evenly around vehicle with same desired $d_{xy,o}$ and height h_o. The S_{total} increase with the increasing of both $d_{xy,o}$ and h_o, however they are both constrained by $d_{\max}$ according to Eq.(6). Then the rate coefficient $\alpha = h/d_{xy}$ is regarded as the optimization parameter in maximization of S_{total}.

For example, three UAVs at (P_1, P_2, P_3) are distributed evenly around vehicle P_G with different α and same distance d, shown in Fig.4(a) and Fig.4(b). S_{total} is obtained by overlapping S_{FOV} of each UAV, while (P_a, P_b, P_c) are the intersection points of S_{FOV}. Then S_{total} can be divided into equal three S without overlapping. For example, the area S for UAV at P_2 consists of triangular area $S_{\Delta P_G P_2 P_b}$, $S_{\Delta P_G P_2 P_a}$ and sector area $S_{P_b P_2 P_a}$ with angle μ. S_{total} is given as,

$$\begin{aligned} & S_{total} = 3S \\ & S = 2S_1 + S_2 \\ & S_1 = \tfrac{1}{2}(\cos\tfrac{\pi}{3} d_{xy} + (r^2 - (sin\tfrac{\pi}{3} d_{xy})^2)^{\frac{1}{2}}) \sin\tfrac{\pi}{3} d_{xy} \\ & S_2 = \tfrac{1}{2} r^2 \mu \\ & \mu = 2\pi - 2(\tfrac{\pi}{6} + \cos^{-1}\tfrac{sin\frac{\pi}{3} d_{xy}}{r}) \end{aligned} \tag{7}$$

where S consists of $2S_1$ and S_2. The S_1 is the triangular area $S_{\Delta P_G P_2 P_b}$ or $S_{\Delta P_G P_2 P_a}$ and S_2 is the sector area $S_{P_b P_2 P_a}$. Besides, the length of green line is d_{xy}, blue line is radius r.

Then the area S is expressed by distance d and rate coefficient α according to Eq.(7), given as,

$$\begin{aligned} S &= (\tfrac{1}{2} + (\alpha^2 - \tfrac{3}{4})^{\frac{1}{2}})\tfrac{\sqrt{3}}{2} d_{xy}^2 + d_{xy}^2 \alpha^2 (\tfrac{5\pi}{6} - \cos^{-1}\tfrac{\sqrt{3}}{2\alpha}) \\ &= \tfrac{d^2}{1+\alpha^2}(\tfrac{\sqrt{3}}{4} + \tfrac{\sqrt{3(\alpha^2 - \frac{3}{4})}}{2} + \alpha^2(\tfrac{5\pi}{6} - \cos^{-1}\tfrac{\sqrt{3}}{2\alpha})) \end{aligned} \tag{8}$$

where γ is assumed to be $45°$ for computation, then $r = h = \alpha d_{xy}$. h and d_{xy} can both be expressed by rate α and d. The maximization of S/d^2 is only related to coefficient α, shown in Fig.5.

The relative area S/d^2 changes with coefficient α, and obviously there is a maximum value of S/d^2. The optimal α_o can be obtained by deriving the equation or finding the abscissa of maximum point as,

$$\alpha_o = \arg\max(S/d^2) \tag{9}$$

The desired UAV formation around ground vehicle is obtained according to α_o and $d_{\max}/\lambda$ as,

$$\begin{aligned} & d_{xy,o} = \frac{(d_{\max}/\lambda)}{(1+\alpha_o^2)^{\frac{1}{2}}} \\ & h_o = \alpha_o \frac{(d_{\max}/\lambda)}{(1+\alpha_o^2)^{\frac{1}{2}}} \end{aligned} \tag{10}$$

where h_o and $d_{xy,o}$ are desired parameters of UAV formation. The formation control scheme of multi-UAVs is proposed to maintain this formation in simple environment.

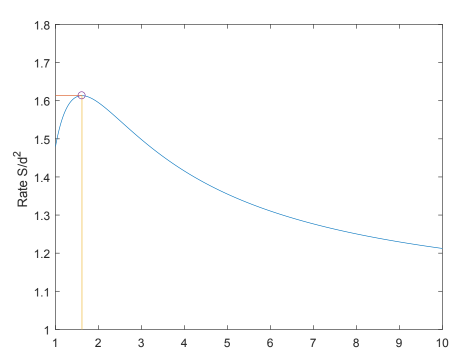


Fig. 5. Coefficient α_o and maximization of coverage areas

B. Formation update scheme in complex environment

The formation control scheme of multi-UAVs is proposed to maintain the original desired formation, while obstacles avoidance method must be utilized and combined with formation scheme in exploration of complex environment. To maintain the original desired formation, the formation scheme is updated according to the need of obstacles avoidance.

To describe the risk of collision in the complex environment, the obstacles or threats are expressed as,

$$\begin{aligned}&\Gamma_l(P) = (\tfrac{x-x_{o,l}}{\rho_{x,l}})^{2p_{x,l}} + (\tfrac{y-y_{o,l}}{\rho_{y,l}})^{2p_{y,l}} + (\tfrac{z-z_{o,l}}{\rho_{z,l}})^{2p_{z,l}}\\&\Gamma_{\min}(P) = min(\Gamma_l(P)), (l=1,2,...,L)\end{aligned} \tag{11}$$

where $\Gamma_l(P)$ is the surface function of lth obstacle in the environment, $(l=1,2,...,L)$. $P=(x,y,z)$ is the position in the environment. $(x_{o,l}, y_{o,l}, z_{o,l})$ are center of lth obstacle in three dimensions. Parameter ρ_l and p_l are utilized to describe the size and shape of lth obstacles.

The $\Gamma_l(P)$ represent the relationship between position P and surface of lth obstacle, then it can describe the risk of collision when UAV at P approaching to lth obstacles. The $\Gamma_{\min}(P)$ represents how close the closet obstacle to UAV at P, then it can describe the need of obstacles avoidance method for UAV at P.

To combine with IFDS method, the formation control scheme is updated according to original desired h_o, $d_{xy,o}$ and $\Gamma_{\min}(P)$. Then the Eq.(10) is updated as,

$$\begin{aligned}&z_{d,i} = (h_o - z_i)(1 - b_z e^{-\Gamma_{\min}(P_i)/c_z})^{a_z} + z_i\\&d_{xy,o} = ((d_{\max}/\lambda)^2 - z_i^2)^{\frac{1}{2}}(1 - b_d e^{-\Gamma_{\min}(P_i)/c_d})^{a_d}\end{aligned} \tag{12}$$

where $z_{d,i}$ is the updated desired flying height of ith UAV when UAV at P_i approaching to obstacle. The desired radial distance $d_{xy,o}$ of ith UAV is updated according to z_i and $d_{\max}/\lambda$. $d_{xy,o}$ decreased if z_i was raised by IFDS method to avoid obstacles, thereby d_i can be still constrained by $d_{\max}/\lambda$.

Then desired location $(x_{d,i}, y_{d,i})$ of ith UAV on xy plane are given as,

$$\begin{aligned}&\begin{bmatrix} x_{d,i} \\ y_{d,i} \end{bmatrix} = \begin{bmatrix} x_G \\ y_G \end{bmatrix} - d_{xy,o}\frac{e_{i+1}+e_{i-1}}{||e_{i+1}+e_{i-1}||}\\&e_i = \frac{P_{xy,i}-P_G}{||P_{xy,i}-P_G||} = [\frac{x_i-x_G}{d_{xy,i}}, \frac{y_i-y_G}{d_{xy,i}}]^T\end{aligned} \tag{13}$$

where $P_{xy,i}$ are location of ith UAV on xy plane. (e_{i+1}, e_{i-1}) represents the relative locations of other two neighbor UAVs for calculating the desired location of ith UAV. It's no need to distinguish the other two neighbor UAVs.

C. Combination of obstacles avoidance method

The IFDS method is utilized to guide UAVs avoid collision. Compared with traditional method, the biggest advantage of IFDS method is its high computation efficiency.

The original velocity vector of UAVs are considered as initial streamlines, while the influence of static obstacles in environment to the initial streamlines are expressed as a modulation matrix, shown in Fig.6. Then original velocity vector are modified by the modulation matrix and regarded as the desired velocity of UAVs. The original general direction of UAV will not be changed by IFDS method.

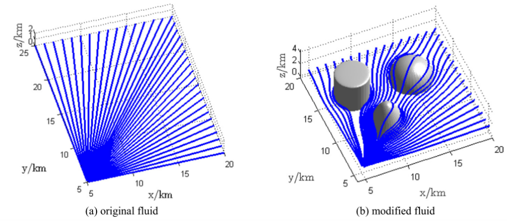


Fig. 6. Origin streamlines and interfered streamlines in complex 3D environment

The desired position of each UAV $P_{d,i} = [x_{d,i}, y_{d,i}, z_{d,i}]^T$ is obtained according to Eq.(12) and Eq.(13), then desired velocity vector $V_{d,i}$ of ith UAV is obtained according to position error, given as,

$$\begin{aligned}&V_{d,i} = f_v(||P_{d,i} - P_i||)\frac{P_{d,i}-P_i}{||P_{d,i}-P_i||}\\&f_v(\xi) = (1 - b_v e^{-\xi/c_v})^{a_v} V_{\max}\end{aligned} \tag{14}$$

Modulation matrix which represents the influence of lth obstacle to velocity vector $V_{d,i}$ of UAV at $P=(x,y,z)$ is given as,

$$\begin{aligned}&\omega_l(P) = \prod_{i=1, i\neq l}^{L} \frac{\Gamma_i(P)-1}{(\Gamma_i(P)-1)+(\Gamma_l(P)-1)}\\&n_l(P) = [\frac{\partial\Gamma_l(P)}{\partial x}, \frac{\partial\Gamma_l(P)}{\partial y}, \frac{\partial\Gamma_l(P)}{\partial z}]^T\\&\mathrm{t}_l(P) = [\frac{\partial\Gamma_l(P)}{\partial y}, -\frac{\partial\Gamma_l(P)}{\partial x}, 0]^T\\&M_l(P) = I - \frac{\omega_l(P)n_l(P)n_l(P)^T}{|\Gamma_l(P)|^{\frac{1}{\delta_l}} n_l(P)^T n_l(P)} + \frac{\omega_l(P)t_l(P)n_l(P)^T}{|\Gamma_l(P)|^{\frac{1}{\sigma_l}} ||t_l(P)|| ||n_l(P)||}\end{aligned} \tag{15}$$

where $M_l(P)$ and $\omega_l(P)$ are modulation matrix and weight coefficient of lth obstacle. $n_l(P)$ and $t_l(P)$ are normal vector and tangent vector. δ_l and σ_l are repulsive and tangential parameter which represent degree of influence. The bigger those two parameters, the earlier UAV will be guided to avoid obstacle. Besides, δ mainly focus on z direction component to raise flying height of UAV, so it is mainly considered.

Velocity vector $V_{d,i}$ is considered as original streamlines of IFDS method. Total modulation matrix $\bar{M}(P)$ represents influence of all obstacles on $V_{d,i}$. $\bar{M}(P)$ and $\bar{V}_{d,i}(P)$ are given as,

$$\begin{aligned}&\bar{M}(P) = \prod_{i=l}^{n} M_l(P)\\&\bar{V}_{d,i}(P) = \frac{\bar{M}(P)V_{d,i}(P)}{||\bar{M}(P)V_{d,i}(P)||}||V_{d,i}(P)||\end{aligned} \tag{16}$$

where $\bar{V}_{d,i}(P)$ is regarded as modified velocity vector of ith UAV at P. To ensure $\bar{V}_{d,i}(P)$ can still maintain the general direction, $\bar{V}_{d,i}(P)$ will not be in opposite direction of $V_{d,i}(P)$, which is $\bar{V}_{d,i}(P) \cdot V_{d,i}(P) > 0$. Besides, $||\bar{V}_{d,i}(P)|| = ||V_{d,i}(P)||$ ensure length of velocity vector be less than maximum velocity $V_{\max}$.

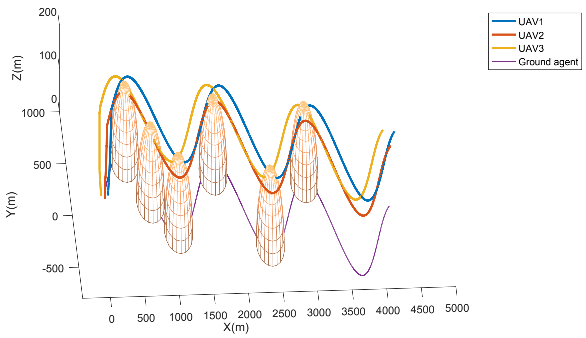


Fig. 7. Trajectory of UAV formation without IFDS method from 3D angle

IV. Simulation

The simulation is conducted with three UAVs and one ground vehicle. The results of simulation can verify the effectiveness of method we proposed by controlling multi-UAVs to maintain the desired formation and avoid obstacles in complex environment. It is simulated in MATLAB R2016a on a PC. The total simulation time is 2000 s and the sampling time interval is 0.2 s.

A. Initial conditions and environment

The trajectory of ground vehicle is given as,

$$\begin{aligned} \mathrm{x}_G(\mathrm{t}) &= 100 + 2\mathrm{t} + 100\mathrm{sin}(0.001\mathrm{t}) \\ \mathrm{y}_G(\mathrm{t}) &= -200 + 400\mathrm{sin}(0.01\mathrm{t}) + 400\mathrm{cos}(0.001\mathrm{t}) \end{aligned} \tag{17}$$

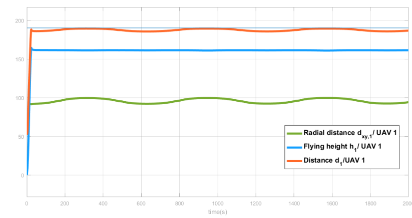
The obstacles is assumed to be passable for ground vehicle. The maximum distance between each UAV and ground vehicle are $d_{\max} = 200m$ and $d_{\max}/\lambda = 190m$. Multi-UAVs take off at initial positions (150,180,0)m, (100,150,0)m and (50,180,0)m.

The desired h_o and $d_{xy,o}$ are obtained according to E-q.(10). γ= 45°. Then optimal rate coefficient is given as $\alpha_o \approx 1.61$. $h_o \approx 161m$ and $d_{xy,o} \approx 100m$.

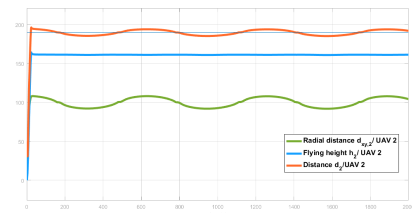
The coefficient (a_z, b_z, c_z) change the desired flying height $z_{d,i}$ in Eq.(12), which are set to (30,0.1,10). The coefficient (a_d, b_d, c_d) are set to (4,0.1,10). In Eq.(14), the coefficient (a_v, b_v, c_v) are set to (40,0.1,10). The maximum speed is $V_{\max} = 10m/s$. δ and σ are set to (0.5,0.2). The maximum height of obstacles are 180m, UAV would collide with the obstacles if the IFDS method was not used.

B. Results of simulation

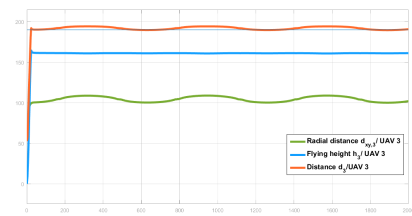
In the first simulation, the IFDS method is not utilized. The trajectory of multi-UAVs and ground vehicle are shown in Fig.7. Obviously, UAVs collide with obstacles while the desired formation is maintained. The d_i, $d_{xy,i}$ and h_i of multi-UAVs are shown in Fig.8. Height h_i of multi-UAVs stay at 161m, and the $d_{xy,i}$ are kept near 100m to maintain the UAV formation.



(a) d_i,$d_{xy,i}$ and flying height h_i of UAV1



(b) d_i,$d_{xy,i}$ and flying height h_i of UAV2



(c) d_i,$d_{xy,i}$ and flying height h_i of UAV3

Fig. 8. Distance between multi-UAVs and ground vehicle when exploring the environment without using IFDS method

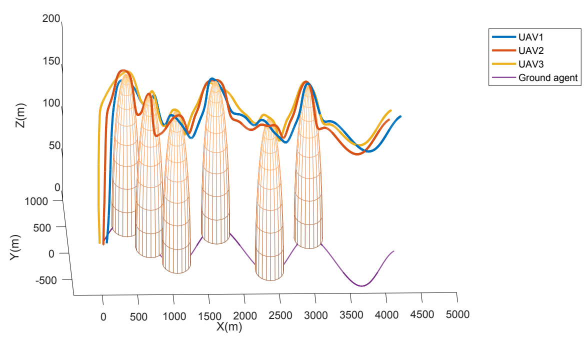
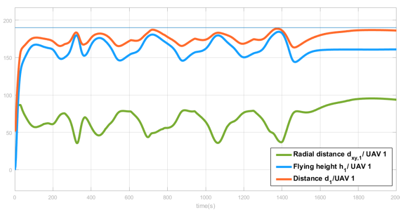


Fig. 9. Trajectory of UAV formation and ground vehicle from 3D angle

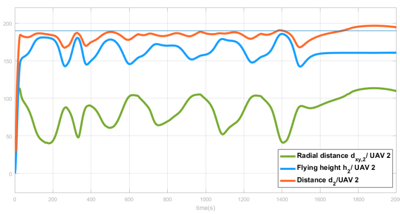
In the second simulation, the IFDS method is utilized and combined with updated formation control scheme. UAVs can avoid obstacles by raising the flying height h_i, while d_i of multi-UAVs are kept under constraint $d_{\max}/\lambda$, shown in Fig.9. In Fig.10(b), the d_i of second UAV exceeds the constraint $d_{\max}/\lambda$ for a while, but it is no more than d_{max}.

V. Conclusion

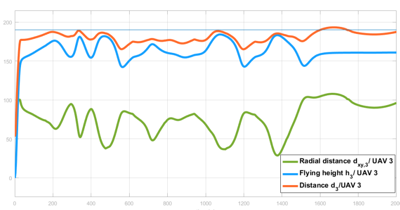
In this paper, the IFDS method will not change the stability of original system and general direction of UAV, which is



(a) d_i,$d_{xy,i}$ and flying height h_i of UAV1



(b) d_i,$d_{xy,i}$ and flying height h_i of UAV2



(c) d_i,$d_{xy,i}$ and flying height h_i of UAV3

Fig. 10. Distance between multi-UAVs and ground vehicle when exploring the complex environment with IFDS method

suitable for maintaining the original formation. The formation control scheme is designed to eliminate the conflict in combination with IFDS method. More kinematic information of neighbor agents can be considered in the design of upper layer of formation control strategy. The controller of UAV can take sliding model control or other advanced algorithm to deal with a more complex system of quadcopter. Next, we can apply this air-ground structure to other applications such as target capturing. Another possible direction is to extend the application on the fixed wing UAV which got kinematic constraints.

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