

Sky Highway Design for Dense Traffic^{*}

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Abstract: The number of Unmanned Aerial Vehicles (UAVs) continues to explode. Within the total spectrum of Unmanned Aircraft System (UAS) operations, Urban Air Mobility (UAM) is also on the way. Dense air traffic is getting ever closer to us. Current research either focuses on traffic network design and route design for safety purpose or swarm control in open airspace to contain large volume of UAVs. In order to achieve a tradeoff between safety and volumes of UAVs, a sky highway with its basic operation for Vertical Take-Off and Landing (VTOL) UAV is proposed, where traffic network, route and swarm control design are all considered. In the sky highway, each UAV will have its route, and an airway like a highway road can allow many UAVs to perform free flight simultaneously. The geometrical structure of the proposed sky highway with corresponding flight modes to support dense traffic is studied briefly one by one. The effectiveness of the proposed sky highway is shown by the given demonstration.

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Keywords: UAV, air traffic, UAM, UTM, swarm.

1. INTRODUCTION

With the on-going miniaturization of motors, sensors, and processors, the number of Unmanned Aerial Vehicles (UAVs) continues to explode. UAVs increasingly play an integral role in many applications in scenarios from the on-demand package delivery to traffic and wildlife surveillance, inspections of infrastructure, search and rescue, agriculture, and cinematography (Balakrishnan (2018)). Within the total spectrum of Unmanned Aircraft System (UAS) operations in the National Airspace System (NAS), Urban Air Mobility (UAM) referring to flight operations to carry personnel and cargo within the geographical limits of an urban metropolis are also on the way (NASA (2019); SESAR (2016)).

Traditionally, the main role of Air Traffic Management (ATM) is to keep prescribed separation between all aircraft by using centralized control. However, it is infeasible for the increasing number of UAVs as the traditional control method is in lack of scalability. To this end, air traffic for UAVs starts to draw the attention of more and more researchers (Gharibi et al. (2016); Devasia and Lee (2016); Mcfadyen and Bruggemann (2017)). A concept, coined as the Internet of Drones (IoD), was proposed in Gharibi et al. (2016), where a conceptual model of how its architecture can be organized was proposed, and the features of an IoD system were described. In Devasia and Lee (2016), based on a proposed pre-established route network, an open-loop UAV operation paradigm was proposed to enable a large number of relatively low-cost UAVs to fly beyond the line of sight. In Mcfadyen and Bruggemann (2017), a concept of network design for a UAS Traffic Management (UTM) system was proposed, where feasible low-level urban airspace regions, candidate network nodes,

and Unmanned Traffic Network (UTN) structure were proposed one by one. Inspired by a swarm in nature, dense traffic study for UAVs is also gaining momentum. In Viragh et al. (2016), some different dense multirotor UAV traffic simulation scenarios in open 2D and 3D space were studied under realistic environments in the presence of sensor noise, communication delay, limited communication range, limited sensor update rate, and finite inertia. Furthermore, in Balázs and Vásárhelyi (2018), a general, decentralized air traffic control solution using autonomous UAVs was proposed, where some difficult dense traffic situations were challenged based on the force-based distributed multi-robot control model. On the one hand, some air traffic studies focus on traffic network design and route design, following the idea of the traditional air traffic transport but with unique differences and challenges. Based on designed traffic networks, the risk to people on the ground will be reduced greatly. On the other hand, some air traffic studies stemmed from swarm control focused on the free flight in open airspace (Chung et al. (2018)). By using swarm control, larger volumes of UAVs can fly at ease in the same airspace.

Motivated by these current studies, a trade-off scheme, called *sky highway*, is proposed for VTOL UAVs, in which traffic network, route, and swarm control design are all considered. The sky highway is a traffic network on which any VTOL UAV should have its own route. Based on this, risk is under control. Unlike the aforementioned networks, UAVs in an airway (a straight-line segment of a route between two nodes) are controlled in a swarm control manner, where the airway like a highway road can allow many UAVs to realize free flight. In this way, the volume of UAVs is increased.

In this paper, the geometrical structure of airways and intersections in the network with corresponding flight

^{*} This work was supported by Beijing Natural Science Foundation [grant number L182037].

modes are designed and studied one by one to support dense traffic. Concretely,

- (i) The geometrical structure of the network rather than abstract lines and nodes is designed to maintain a certain distance between two UAVs on two carriageways (Contribution i).
- (ii) A highway mode is proposed for the airway flight, where a finishing line rather than several waypoints are proposed to avoid a potential traffic jam (Contribution ii).
- (iii) Also, the highway mode is applied to a type of intersections. For another type of intersection, a rotary island mode is proposed. With these two modes, the UAV traffic flow can be increased greatly (Contribution iii).

2. PROBLEM FORMULATION

In this section, a traffic network model is introduced first. Then, the objective of this paper is proposed.

2.1 General Traffic Network Model

The airspace is structured similarly to the road network in cities. Because of the characteristic of the airspace, the airlines could be as shown in Fig. 1. A general traffic network model can be formulated by using the graph theory Devasia and Lee (2016). Similar to the idea found in Gharibi et al. (2016), UAVs are only allowed inside the following three kinds of areas: *airways* which play a similar role to roads, *intersection nodes* that connect at least two airways, *termination nodes* which connect at least one airway where UAVs fly in and out of the network.

2.2 Objective

Some basic principles are provided to guide the traffic network design.

- (i) Every VTOL UAV has its route.
- (ii) UAVs should not collide with each other, so they should be separated at a certain distance. With such a distance $r_a > 0$, two UAVs do not need to take extra effort to avoid each other.
- (iii) UAVs should not fly outside of airways.
- (iv) Every UAV can have different velocities with a setting turning radius.

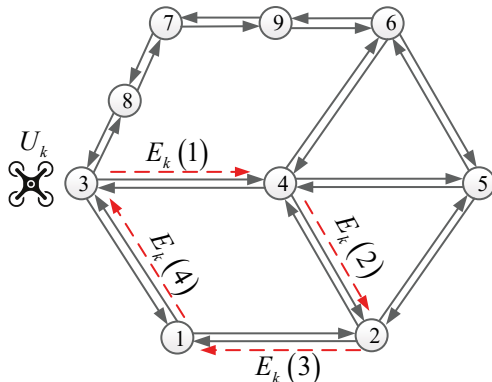


Fig. 1. Traffic network

- (v) UAVs can be allocated different priorities.

Based on these basic principles, an air traffic network named *sky highway* is designed for *dense traffic*. The dense traffic is denser than the current civil aviation transportation. It is similar to the traffic in highways for cars, which allows many UAVs to fly in the same airway and then to pass an intersection. Obviously, the traffic network general model shown in Fig. 1 is too abstract for dense traffic. So, based on this general model, the objective of this paper is to further design the structure of airways and intersections and include as well their corresponding flight modes, which can support dense traffic. For simplicity, only all airways and intersections at the same altitude are focused on, which will be extended to different altitudes in the future.

3. AIRWAY AND INTERSECTION DESIGN FOR DENSE TRAFFIC

In this section, the structure of airways and intersections with corresponding flight modes for supporting dense traffic are studied one by one.

3.1 Airway Design and Flight Mode

Airway Design An airway is designed as shown in Fig. 2. The i th *airway* denoted by $W_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}]}$ is a set of cuboid (length $l_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}]} > 0$, width $2r_{AW} + r_{IS} > 0$, height $h_{AW} > 0$), which is divided into three parts, two *carriageways* for traffic traveling in opposite directions, namely $W_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}], \text{left}}$, $W_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}], \text{right}}$ (length $l_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}]} > 0$, width $r_{AW,i} > 0$, height $h_{AW} > 0$), separated by an *isolation strip* also in the form of a cuboid, namely, $W_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}], \text{iso}}$ (length $l_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}]} > 0$, width $r_{IS} > 0$, height $h_{AW} > 0$). The line segment $[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}]$ is the center line at the middle height of the airway, where $\mathbf{p}_{s,i}, \mathbf{p}_{e,i} \in \mathbb{R}^3$ are the starting point and the ending point, respectively. So,

$$l_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}]} = \|\mathbf{p}_{s,i} - \mathbf{p}_{e,i}\|.$$

Airways should be designed such that two UAVs in two different carriageways are separated at a distance $r_a > 0$. This implies two UAVs on two carriageways do not need to avoid each other. Here, two different carriageways may be in one airway or two different airways. Before proceeding, the distance between two sets is defined. The distance between set S_1 and set S_2 is defined as

$$d(S_1, S_2) \triangleq \min_{\mathbf{x} \in S_1, \mathbf{y} \in S_2} \|\mathbf{x} - \mathbf{y}\|.$$

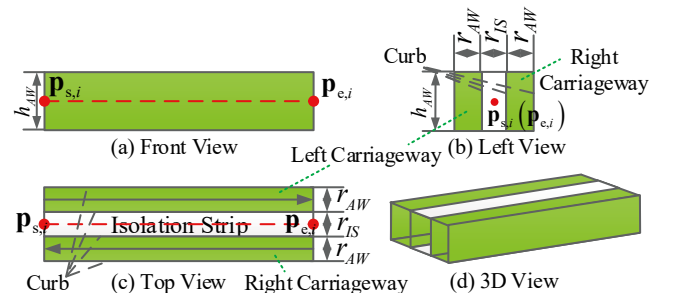


Fig. 2. Airway structure

(1) When two different carriageways are in the same airway, the isolation strip plays an important role. A result is given in *Proposition 1*.

Proposition 1. Suppose the airway structure is shown in Fig. 2. For the i th airway, if

$$r_{IS} > r_a \quad (1)$$

then

$$d(W_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}], \text{left}}, W_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}], \text{right}}) > r_a. \quad (2)$$

(2) When two different carriageways are in two different airways, the two airways should be separated at a distance $r_a > 0$. A result is given in *Proposition 2*.

Proposition 2. Suppose the airway structure is shown in Fig. 2. For the i th and the j th airways, if

$$d([\mathbf{p}_{s,i}, \mathbf{p}_{e,i}], [\mathbf{p}_{s,j}, \mathbf{p}_{e,j}]) > r_a + \sqrt{h_{AW}^2 + (2r_{AW} + r_{IS})^2} \quad (3)$$

then

$$d(W_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}], \text{left}}, W_{[\mathbf{p}_{s,j}, \mathbf{p}_{e,j}], \text{right}}) > r_a, i \neq j. \quad (4)$$

Proof. As shown in Fig. 3, let $\mathbf{p}_i \in W_{[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}]}$ and $\mathbf{p}_j \in W_{[\mathbf{p}_{s,j}, \mathbf{p}_{e,j}]}$ be written as

$$\mathbf{p}_i(t_1, \mathbf{c}_i) = \mathbf{p}_{s,i} + \mathbf{n}_i t_1 + \mathbf{c}_i \quad (5)$$

$$\mathbf{p}_j(t_2, \mathbf{c}_j) = \mathbf{p}_{s,j} + \mathbf{n}_j t_2 + \mathbf{c}_j. \quad (6)$$

Here, $\mathbf{n}_i = \frac{\mathbf{p}_{e,i} - \mathbf{p}_{s,i}}{\|\mathbf{p}_{e,i} - \mathbf{p}_{s,i}\|}$, $\mathbf{n}_j = \frac{\mathbf{p}_{e,j} - \mathbf{p}_{s,j}}{\|\mathbf{p}_{e,j} - \mathbf{p}_{s,j}\|}$, $t_1 \in [0, \|\mathbf{p}_{e,i} - \mathbf{p}_{s,i}\|]$, $t_2 \in [0, \|\mathbf{p}_{e,j} - \mathbf{p}_{s,j}\|]$ and $\mathbf{c}_i, \mathbf{c}_j \in F \subset \mathbb{R}^2$, where F is a cross section of the airway perpendicular to line segment $[\mathbf{p}_{s,i}, \mathbf{p}_{e,i}]$ shown in Fig. 3.

Based on the relation (5) and (6), the conclusion can be drawn. \square

Flight Mode For dense traffic, a *highway mode* is proposed. A carriageway has several lanes but does not require UAVs on lanes one by one, like trains on a railway. UAVs under decentralized control are attracted by a finishing line at the end of the airway rather than several waypoints (as shown in Fig. 4). Once approaching the finishing line, it will switch to another airway, for example, via an intersection. So, the principle (i) in *Section 2.2* is satisfied. UAVs should repel each other if their distance is too short, for example, by using the artificial potential field method. Also, the curbs (as shown in Fig. 2) are required to repel UAVs to keep them within the carriageway. So principles (ii) and (iii) are satisfied. If UAVs have different velocities, then the fast UAV and the slow UAV will interact with each other according to a certain protocol. For example, a protocol is based on the artificial potential field method. Then the fast UAV and slow UAV will often change their flight directions rather than only slow down the fast one.

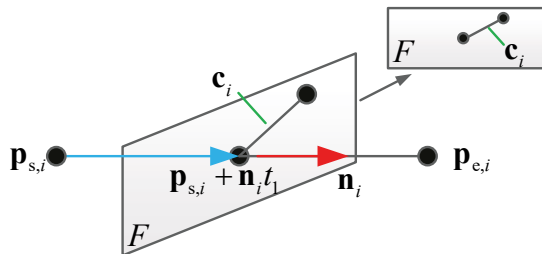


Fig. 3. Position representation in an airway

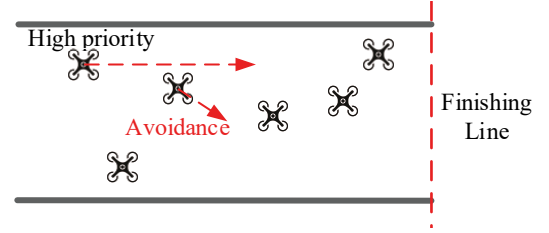


Fig. 4. Highway mode

Generally, the fast one will overtake the slow one. Then, principle (iv) is satisfied. If a UAV with a high priority has to overtake the slow UAV, then the UAV with a high priority can keep the same velocity, but the UAVs with lower priorities should make avoidance.

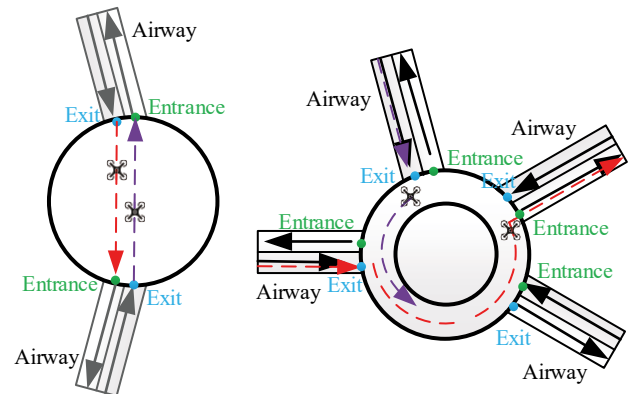
The highway mode is suitable for dense traffic for the following reasons. (i) The airspace is utilized sufficiently. (ii) The designed finishing line will avoid the traffic jam at the end of the airway because the velocities of UAVs are aligned like birds flying in the sky (Dutta (2010)). (iii) In order to perform overtaking, the fast one can often frequently change its direction a little bit to avoid the slow one rather than only reduce its speed.

3.2 Intersection Design and Flight Mode

Intersection Classification An *intersection* connects at least two airways. As shown in Fig. 5, there are two cases.

- (1) An intersection, called a *connection* or *azimuth connection* is connected with two airways to change azimuth, because only all airways and intersections on the same altitude are focused on. For example, Nodes 1, 7, 8, 9 are shown in Fig. 1.
- (2) An intersection is used as a hub through which UAVs can select different airways to go. It connects with more than two airways, called a *hub*, shown in Fig. 5(b), such as Nodes 2, 4, 5, 6 shown in Fig. 1. It is required that all airways connect with a hub intersection.

In the following, some basic principles on intersections are described. Furthermore, two modes for the two types of intersections are proposed.



(a) Highway mode for a connection (b) Rotary island mode for a hub

Fig. 5. Modes for two types of intersections

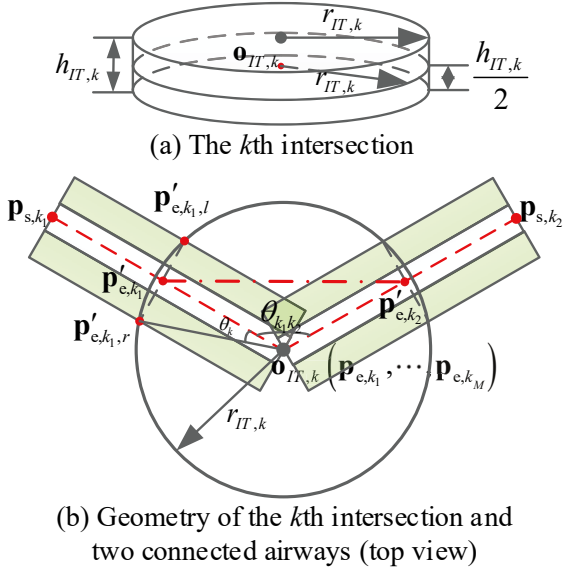


Fig. 6. The i_1 th and i_2 th airways are connecting with a hub intersection

Intersection Design For the k th intersection, as shown in Fig. 6, suppose the center lines $[\mathbf{p}_{s,k_j}, \mathbf{p}_{e,k_j}]$ of M airways intersect at a point $\mathbf{o}_{IT,k}$, $j = 1, \dots, M$, namely

$$\mathbf{o}_{IT,k} = \mathbf{p}_{e,k_1} = \dots = \mathbf{p}_{e,k_M}$$

where k_j means the j th airway of the k th intersection. The intersection is denoted by I_{k_1, k_2, \dots, k_M} , which is a set of a cylinder with center $\mathbf{o}_{IT,k}$, radius $r_{IT,k}$ and height $h_{IT,k} \geq h_{AW}$, $M \in \mathbb{Z}_+$. We hope that the minimum distance between any pair of airways outside of an intersection should be greater than r_a . Moreover, the minimum turning radius for all UAVs is $r_t > 0$. For the j_1 th and the j_2 th airways of the k th intersection, the requirement can be formulated as

$$d(W_{out, k_{j_1}}, W_{out, k_{j_2}}) > r_a, j_1 \neq j_2, j_1, j_2 = 1, \dots, M \quad (7)$$

where

$$W_{out, k_{j_1}} = W_{[\mathbf{p}_{s, k_{j_1}}, \mathbf{p}_{e, k_{j_1}}]} \cap \bar{I}_{k_1, k_2, \dots, k_M}$$

$$W_{out, k_{j_2}} = W_{[\mathbf{p}_{s, k_{j_2}}, \mathbf{p}_{e, k_{j_2}}]} \cap \bar{I}_{k_1, k_2, \dots, k_M}$$

and $\bar{I}_{k_1, k_2, \dots, k_M} = \mathbb{R}^3 - I_{k_1, k_2, \dots, k_M}$ is the complementary set of I_{k_1, k_2, \dots, k_M} . For hub intersections and connections, we have the result shown in *Proposition 3*.

Proposition 3. For the k th intersection I_{k_1, k_2, \dots, k_M} , line segments $[\mathbf{p}_{s, k_j}, \mathbf{p}_{e, k_j}]$ are parallel to the level ground and at the same altitude, $j = 1, \dots, N_k$. If the intersection radius satisfies

$$r_{IT,k} > \max_{j_1 \neq j_2, j_1, j_2 = 1, \dots, M} \left(\frac{r_a + \sqrt{h_{AW}^2 + (2r_{AW} + r_{IS})^2}}{2 \cos \theta_k \sin \frac{\theta_{k_{j_1} k_{j_2}}}{2}}, r_t \right) \quad (8)$$

then (7) holds and the turning radius is satisfied, where

$$\theta_{k_{j_1} k_{j_2}} = \arccos \frac{(\mathbf{p}_{e, k_{j_1}} - \mathbf{p}_{s, k_{j_1}})^T (\mathbf{p}_{e, k_{j_2}} - \mathbf{p}_{s, k_{j_2}})}{\|\mathbf{p}_{e, k_{j_1}} - \mathbf{p}_{s, k_{j_1}}\| \|\mathbf{p}_{e, k_{j_2}} - \mathbf{p}_{s, k_{j_2}}\|} \quad (9)$$

$$\theta_k = \arcsin \frac{r_{AW} + r_{IS} / 2}{r_{IT,k}}, j_1 \neq j_2, j_1, j_2 = 1, \dots, M. \quad (10)$$

Proof. According to (8), the minimum turning radius is satisfied first. Without loss of generality, we take $W_{[\mathbf{p}_{s, k_1}, \mathbf{p}_{e, k_1}]}$ and $W_{[\mathbf{p}_{s, k_2}, \mathbf{p}_{e, k_2}]}$ as an example. As shown in Fig. 6, $\mathbf{p}'_{e, k_1, l}, \mathbf{p}'_{e, k_1, r}, \mathbf{p}'_{e, k_1}$ are all on the middle level plane containing $[\mathbf{p}_{s, k_1}, \mathbf{p}_{e, k_1}]$. First, the 1st and 2nd airways can be divided into two parts as

$$W_{[\mathbf{p}_{s, k_1}, \mathbf{p}_{e, k_1}]} = W_{[\mathbf{p}_{s, k_1}, \mathbf{p}'_{e, k_1}]} \cup W_{[\mathbf{p}'_{e, k_1}, \mathbf{p}_{e, k_1}]}$$

$$W_{[\mathbf{p}_{s, k_2}, \mathbf{p}_{e, k_2}]} = W_{[\mathbf{p}_{s, k_2}, \mathbf{p}'_{e, k_2}]} \cup W_{[\mathbf{p}'_{e, k_2}, \mathbf{p}_{e, k_2}]}.$$

Obviously, we have $W_{[\mathbf{p}'_{e, k_1}, \mathbf{p}_{e, k_1}]} \subseteq I_{k_1, k_2, \dots, k_M}$ and $W_{[\mathbf{p}'_{e, k_2}, \mathbf{p}_{e, k_2}]} \subseteq I_{k_1, k_2, \dots, k_M}$. Since

$$W_{out, k_1} \subset W_{[\mathbf{p}_{s, k_1}, \mathbf{p}'_{e, k_1}]}, W_{out, k_2} \subset W_{[\mathbf{p}_{s, k_2}, \mathbf{p}'_{e, k_2}]} \quad (11)$$

the inequality

$$d\left(W_{[\mathbf{p}_{s, k_1}, \mathbf{p}'_{e, k_1}]}, W_{[\mathbf{p}_{s, k_2}, \mathbf{p}'_{e, k_2}]}\right) > r_a \quad (12)$$

implies

$$d(W_{out, k_1}, W_{out, k_2}) > r_a. \quad (13)$$

Based on this, we focus on the proof of the condition (12). According to *Proposition 2*, we can conclude this proof. \square

Remark 1. From condition (8), $\theta_{k_{j_1} k_{j_2}}, r_a, h_{AW}, r_{AW}, r_{IS}$ are constants, and $\cos \theta_k \rightarrow 1$ as $r_{IT,k}$ is increasing according to (10). Therefore, $r_{IT,k}$ can always be found for (8) if it is large enough. To avoid an $r_{IT,k}$ which is too large, $\theta_{k_{j_1} k_{j_2}}$ should not be too small.

Highway Mode for a Connection It can be considered that two carriageways for traffic traveling in opposite directions are established in connection. So, basic principles are satisfied in the connection. Similarly, as shown in Fig. 5(a), all UAVs fly towards their next airways in the highway mode. For example, as shown in Fig. 7, we hope that the minimum distance between any pair of UAVs inside of an intersection should be separated at r_a . Let $\mathbf{p}''_{e, k_j, l}$ and $\mathbf{p}''_{e, k_j, r}$ be the intersection points of the intersection $I_{k_1 k_2}$ and the isolation strip of the j th airway on the middle level plane containing $[\mathbf{p}_{s, k_j}, \mathbf{p}_{e, k_j}]$, $j = 1, 2$. Obviously, the distance between line segment $[\mathbf{p}''_{e, k_1, l}, \mathbf{p}''_{e, k_2, r}]$ and line segment $[\mathbf{p}''_{e, k_1, r}, \mathbf{p}''_{e, k_2, l}]$ is the minimum distance for any pair of UAVs from two different carriageways inside an intersection. If such a distance is greater than r_a , then the distance between any pair of UAVs from two different carriageways inside an intersection is greater than r_a . The result is given in *Proposition 4*.

Proposition 4. For the azimuth connection $I_{k_1 k_2}$ shown in Fig. 7, if

$$r_{IS} > \frac{r_a}{\sin \frac{\theta_{k_1 k_2}}{2}} \quad (14)$$

then

$$d([\mathbf{p}''_{e, k_1, l}, \mathbf{p}''_{e, k_2, r}], [\mathbf{p}''_{e, k_1, r}, \mathbf{p}''_{e, k_2, l}]) > r_a. \quad (15)$$

Proof. First, it is obvious that

$$[\mathbf{p}''_{e, k_1, l}, \mathbf{p}''_{e, k_2, r}] \parallel [\mathbf{p}''_{e, k_1, r}, \mathbf{p}''_{e, k_2, l}]. \quad (16)$$

So, we have

$$\begin{aligned}
& d([\mathbf{p}_{e,k_1,l}''', \mathbf{p}_{e,k_2,r}'''], [\mathbf{p}_{e,k_1,r}''', \mathbf{p}_{e,k_2,l}''']) \\
&= d(\mathbf{p}_{e,k_1,l}''', [\mathbf{p}_{e,k_1,r}''', \mathbf{p}_{e,k_2,l}''']) \\
&= r_{IS} \sin \angle \mathbf{p}_{e,k_1,l}''', \mathbf{p}_{e,k_1,r}''', \mathbf{p}_{e,k_2,l}'''. \quad (17)
\end{aligned}$$

Since the triangle $\triangle \mathbf{p}_{e,k_1,r}''', \mathbf{sp}_{e,k_1}'$ is similar to the triangle $\triangle \mathbf{o}_{IT,k}, \mathbf{so}_{IT,k}'$, we have

$$\angle \mathbf{p}_{e,k_1,l}''', \mathbf{p}_{e,k_1,r}''', \mathbf{p}_{e,k_2,l}'' = \frac{\theta_{k_1 k_2}}{2} \quad (18)$$

where $\theta_{k_1 k_2}$ is shown in Fig. 6(b). According to (17) and (18), if (14) is satisfied, then (15) holds. \square

Rotary Island Mode for a Hub A rotary island, as shown in Fig. 5(b), can be considered as a bent carriageway. In the rotary island mode, all UAVs entering the intersection will perform a clockwise or anticlockwise rotation until they fly at the entrance to the next airway. Other operations are similar to those in the highway mode. Hence, basic principles can be satisfied in a hub. One intersection can take several UAVs in it at the same time. Applying the highway mode directly to a hub will cause the jam because of the difference among the flight directions of UAVs in a hub. In the rotary island mode, the velocity of a UAV aligns with those around it, which is similar to the situation of birds flying in the sky. It allows more UAVs in the hub simultaneously, in addition, to make it easier to avoid a jam.

4. EXPERIMENTS AND RESULTS

We design a set of experiments to demonstrate the effectiveness of the designed sky highway above. The video is available at <https://youtu.be/WDhNroCMD04>.

4.1 Simulation Experiment

The controller design is based on Matlab R2017b and Simulink 9.3, which is used for generating speed commands of every UAV based on the artificial potential field method

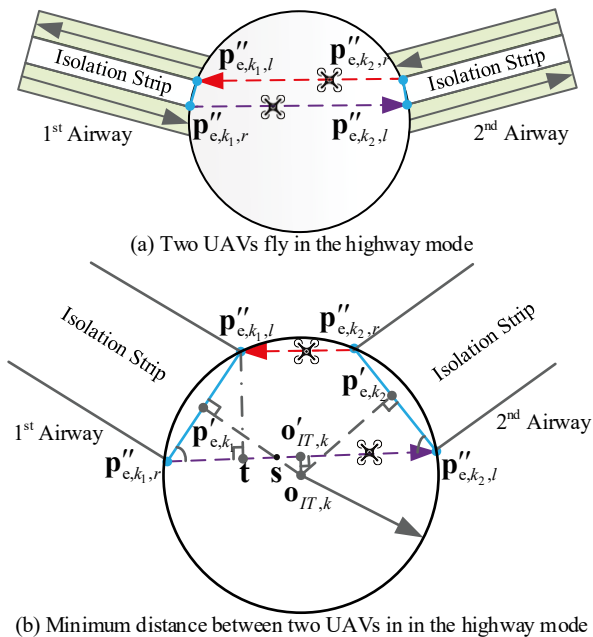


Fig. 7. A connection

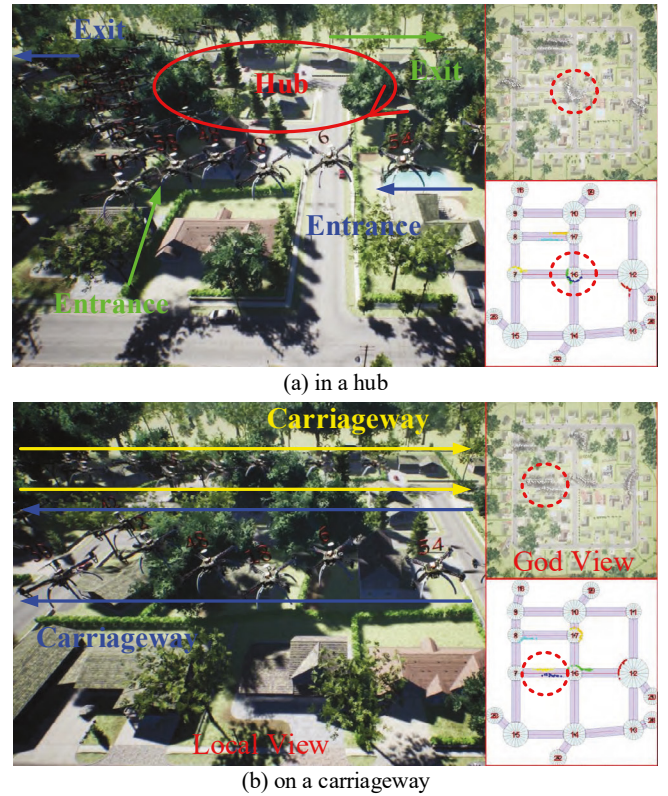


Fig. 8. Sky highway simulation

found in Quan (2017). The model simulator configures parameters of UAVs and generates sensor data to the controller via the UDP communication network. The 3D viewer is based on Unreal Engine 4, which is used for displaying real-time flight performance with high-quality screens.

Build a traffic network shown in Fig. 8, assuming that $r_a = 3$ m, $r_{AW} = h_{AW} = 9$ m. There are eighty UAVs with different routes and colors. Each UAV is required to depart from its airport and then pass the nodes in its route according to its specified sequence. During the whole process, UAVs are only permitted to fly within airways.

As shown in Fig. 8, the airways and intersections are designed within the geometrical structure of the sky highway generation module. The width r_{IS} of each isolation strip satisfies conditions (1) and (3), and airways connected with azimuth connections satisfy the condition (14). In addition, each intersection radius satisfies the condition (8). As shown in Fig. 8(a), we track UAVs labeled blue color. UAVs in blue and green all enter Node 16 and leave through different carriageways. They perform a clockwise rotation in rotary island mode so that the UAV traffic flow can be increased greatly. As shown in Fig. 8(b), UAVs in blue enter the carriageway connecting Node 16 to Node 7 in the highway mode. Unlike in a line, some UAVs fly neck by neck, so the airspace is utilized sufficiently in the carriageway. Meanwhile, UAVs in blue do not affect the UAVs in yellow on the other carriageway in the same airway because of the isolation strip. Finally, all UAVs complete their routes, and they always keep a safe distance from others, as shown in Fig. 9.

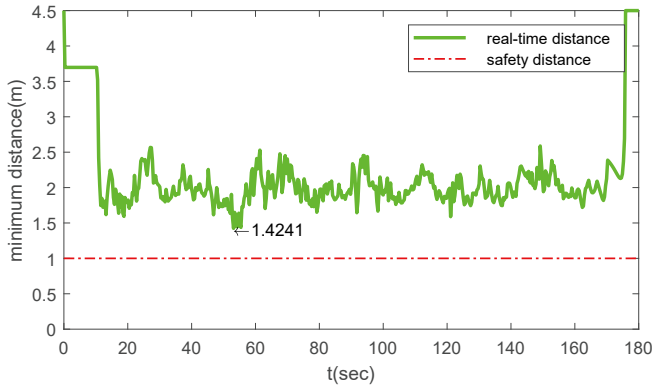


Fig. 9. Minimum pairwise distance of UAVs at each time

4.2 Flight Experiment

An experiment is carried out in a laboratory room with an OptiTrack motion capture system installed, which provides the ground truth of the positions and orientations of UAVs. The laptop mainly includes four modules: the geometrical structure of the sky highway generation, flight mode switching, plotting, and UAV control. Build a traffic network shown in Fig. 10. There are six UAVs with different routes and colors.

We track UAV 3 by the dotted circle as shown in Fig. 10(a). After take-off, it enters the carriageway connecting Node 6 to Node 4 in the highway mode at 14.48 second. As shown in Fig. 10(b), Node 3 is a hub, and UAVs 2, 4, and 6 also enter this intersection at 35.22 second. They all perform a clockwise rotation in rotary island mode. Finally, all UAVs complete their routes at 94.84 second, and they always keep a safe distance from others, as shown in Fig. 10(c).

5. CONCLUSIONS AND FUTURE WORK

The geometry-based structure of airways and intersections is designed as a preliminary study on sky highway design. To maintain a certain distance between two UAVs, we propose related basic conditions for airways and intersections parameters. The highway mode is applied to airways for dense traffic. As for a hub or an intersection, the proposed highway and rotary island modes are applied concerning the number of airways connected. Finally, the effectiveness of the proposed sky highway is shown by the given demonstration.

However, there are still many challenges or work deserved to explore. The 2D structure can be advanced to a more reasonable and efficient 3D structure. The geometric parameters of airways and intersections can take more consideration into the impact of some practical applications, such as environment (e.g., winds), communication (e.g., delay or packet loss), the flight capability of UAVs (e.g., maximum speed or turning radius), etc. More advanced traffic rules and principles, such as overtaking or switching lines, are worthy of further study. As for UAVs' control strategy to such a structure, the avoidance of inter-agent conflicts and local minima is another challenge. The future work mentioned above will help in developing the existing

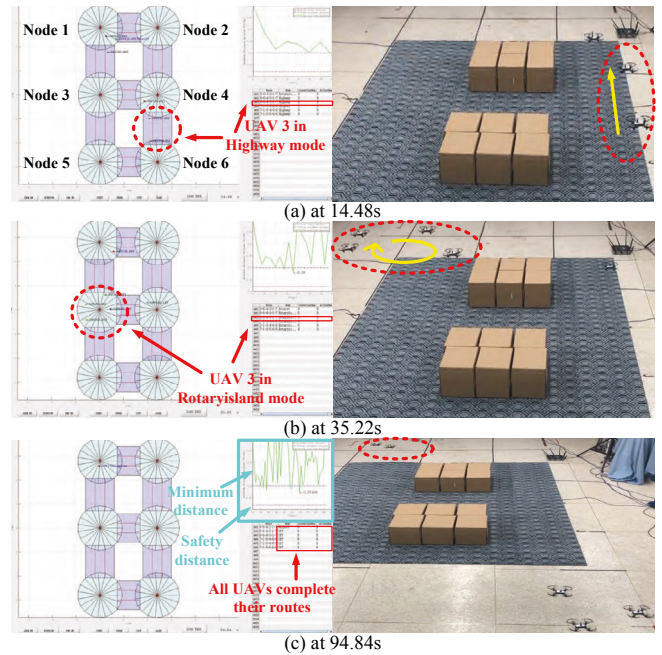


Fig. 10. The position, velocity and mode of each UAV during the whole flight experiment

air traffic structure and assist in having better quality, reality, and efficiency of management.

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